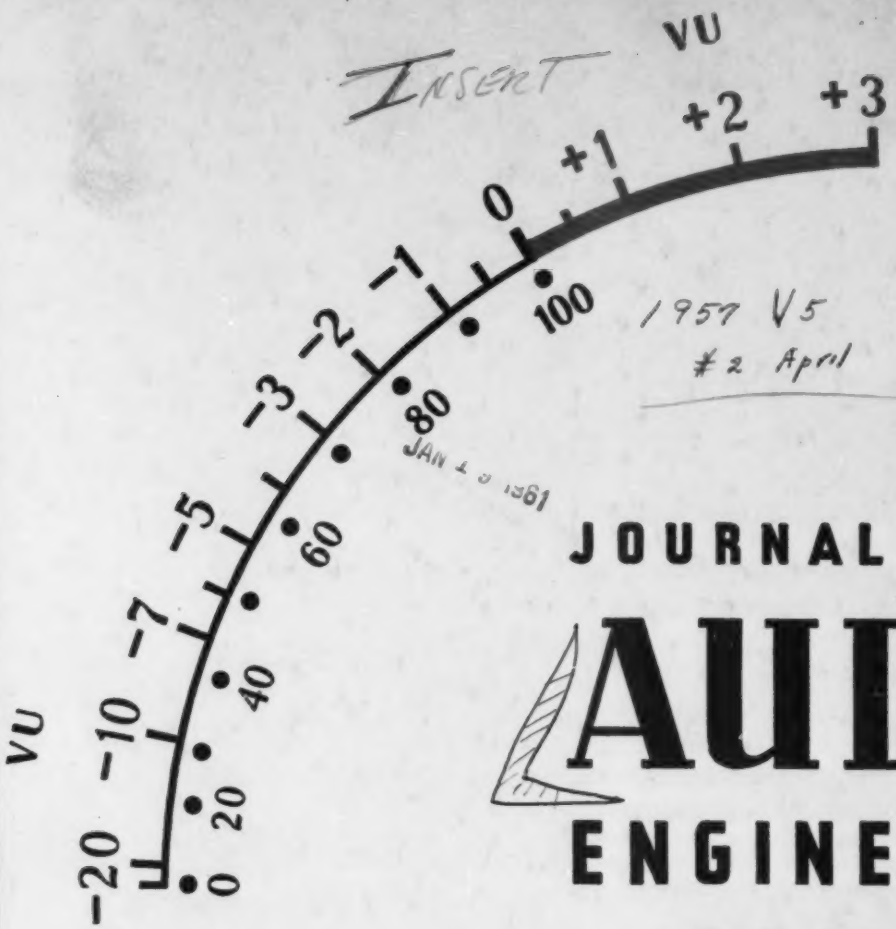

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JOURNAL OF THE AUDIO ENGINEERING SOCIETY

1957

VOLUME 5 NUMBER 2 APRIL 1957

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Date of Publication: June 10, 1958

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Journal of the Audio Engineering Society, Volume 5, Number 2, April 1957. Published quarterly by the Audio Engineering Society and supplied to all members in good standing. Publication office, 104 Liberty Street, Utica, N. Y. Executive and editorial office, P. O. Box 12, Old Chelsea Station, New York 11, N. Y. Entered as second class matter at the post office at Utica, N. Y. Subscription to nonmembers, $8 per year. Address manuscripts and all editorial correspondence to George Horiuchi, Columbia University, 632 West 125 Street, New York 27, N. Y.

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The Journal is indexed in the *Applied Science & Technology Index.*

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Impedance — Matched or Optimum?*

WILLIAM B. SNOW†
1011 Georgiana Avenue, Santa Monica, California

The term "matched impedance" is used frequently, but not always with the same meaning. A matched impedance is not the ideal condition in many cases, and the best impedance relationship between two circuits which are to be connected together depends upon the circumstances of the application. The paper discusses the origin of the matched impedance concept, and gives examples of situations where it is optimum. It then shows additional circuit conditions where other impedance relationships prove to be optimum.

INTRODUCTION

THE MATERIAL of this paper is tutorial in nature rather than new. Its purpose is to provide a summary of information which is now spread through various publications, spanning many years, and to emphasize useful concepts of a fundamental nature which are frequently not thoroughly grasped during an engineer's student days. It is a companion paper to one published in a previous issue of the JOURNAL.[1]

The Winston dictionary defines the word "match" as follows: "Anything that agrees with or is exactly like another thing." This is the definition which the author has always had in mind for a matched impedance, but the following definition appears in the new "Dictionary of Physics and Electronics"[2]—"Impedance which will cause maximum power transfer." This is synonymous with the conjugate impedance, whereas the former definition is synonymous with the image impedance. For resistive circuits, which predominate in audio frequency work, they are the same. In this paper matched impedance will be taken to be image impedance; i.e., the impedance looking both ways from the junction is the same.[3]

HISTORY

The term "matched impedance" is used today very frequently where it is not applicable. Most of the time what is really meant is that the driving circuit is connected to a receiving circuit impedance which gives the most effective total end result. It is the author's feeling that it is undesirable to consistently misuse a scientific term. When this is done the meaning of the term becomes so cloudy as to be substantially useless, and the thinking of those people who misuse it becomes equally cloudy from the standpoint of appreciating what it is they are trying to do.

Where did the concept of the matched impedance originate? Historically it probably arose among telephone engineers in the days before amplifiers were available. The telephone transmitter, being actuated by the voice, has a maximum possible output determined by the strictly limited voice power, and it was necessary to transfer as much of this power as possible to the telephone line. This maximum power transfer occurred with matched impedances, as will be explained in more detail in the next section. Consequently the concept of matched impedance as the most favorable condition was logically established.

MAXIMUM POWER TRANSFER

In Fig. 1 a very simple circuit is shown in which a generator with resistance R_G feeds a load of resistance R_L. To make the arithmetic simple, the generator is assumed to have a voltage of 1 volt, and a resistance of 1 ohm. The figure shows a number of the resulting electrical conditions.

* Paper presented before the Fifth Annual West Coast Convention of the Audio Engineering Society, Los Angeles, February 7, 1957. Manuscript received May 14, 1957.

† Consulting Engineer.

[1] W. B. Snow, "Audio-Frequency Input Circuits," *J. Audio Eng. Soc.*, 1, (1953).

[2] International Dictionary of Physics and Electronics, D. Van Nostrand Co., Inc., New York, 1956.

[3] Transmission Networks and Wave Filters, T. E. Shea, D. Van Nostrand Co., Inc., New York, 1929, p. 81.

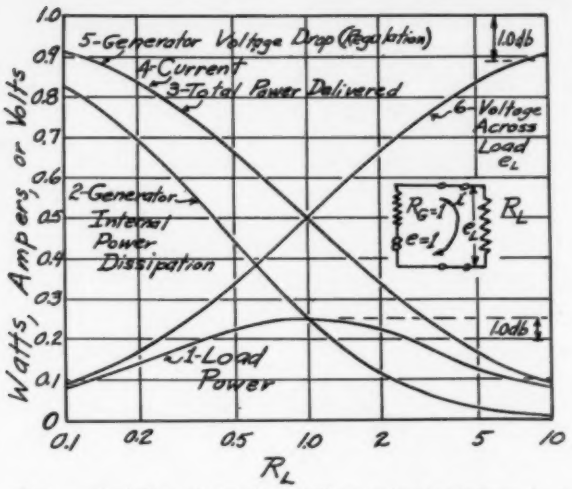

FIG. 1. Variation of circuit conditions as load resistance R_L is varied. Although the scales shown are direct reading, they can be read as ratio scales with abscissa R_L/R_G and ordinates as $W/W_{\text{short circuit}}$, $I/I_{\text{short circuit}}$, $E/E_{\text{open circuit}}$.

The power furnished to the load is given by curve 1 at the bottom. This reaches a maximum of 0.25 watt when the load resistance is equal to, or matches, the generator resistance. It will be noticed that attainment of this condition is not very critical, because any load resistance from about one-third to about three times the generator resistance will receive power within 1 db of maximum.

There is an optimum direction of mismatch, however. Curve 2 shows the power dissipated inside the generator itself, as the load resistance is varied, and curve 3 gives the corresponding total power which the primary source must deliver. When the load power is maximum at 0.25 watt the generator power is also 0.25 watt, and the total is 0.5 watt. Thus the matched condition which gives maximum power transfer results in an efficiency of only 50%. The curve for generator internal power dissipation rises steeply for load resistances lower than the generator resistance, but falls to low values above the matched impedance point. Consequently if a mismatch is to be used it should be in the direction of having the load resistance higher than the generator resistance; this will make smaller demands on the primary power source, most of the power will be delivered to the load, and the efficiency will be higher. As the load impedance is reduced below the matched value the efficiency becomes extremely low.

REGULATION

The voltage across the load (curve 6) will be seen to be one-half the generator voltage at optimum power transfer, and it is changing rapidly as the load resistance varies. Conversely, of course, one-half of the generated voltage (curve 5) is used up as voltage drop in the generator itself and the regulation as a function of load changes is therefore poor under these conditions.

REFLECTIONS

Another strong reason for matching impedance also arises from telephone practice. When long electrical circuits are terminated in unmatched impedances, electrical reflections are produced which cause irregularities in transmission, and show up as echoes which interfere with speech perception because of the time delay between the signal and echo. Reflection losses also are objectionable in filter and electrical network circuits for the irregularities in response they produce, although here the time delays are not ordinarily appreciable to the human ear. In such cases the matched impedance is the optimum.

In microwave radio frequency engineering where most circuits are "electrically long" this is a continuing problem. The equipment ratings expressed as standing wave ratio are a method of indicating the strength of reflections.

EFFECTS OF FREQUENCY

In Fig. 1 purely resistive circuits were discussed and therefore frequency did not enter the problem. When the circuits become reactive, things are not so straightforward. Figure 2 illustrates some typical examples. Condition "A" is that of a matched circuit, according to the author's definition. The generator contains an inductive reactance of 1 ohm at frequency f_o, and the load therefore also contains a similar reactance. This figure shows that the power de-

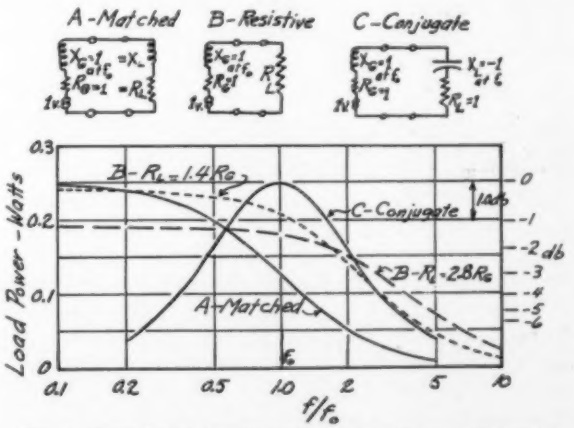

FIG. 2. Examples of circuits containing reactance. The absolute value of the reactance equals the generator resistance R_G at frequency f_o.

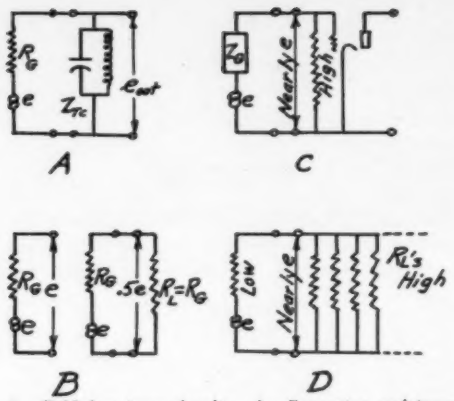

FIG. 3. Bridging type circuits. A—Generator resistance high. B, C, D—Generator resistance low.

livered to the load, now a function of frequency, is nearly 0.25 watt at very low frequencies, but is reduced to 0.125 watt at f_o. Above f_o, which is often referred to as the "half-power point" or "–3 db point," the curve approaches a –6 db-per-octave slope.

The two curves "B" represent the condition where a purely resistive load is employed. In one case the load resistance equals the generator impedance at f_o (1.4 R_G) and in the second case it equals twice this value. The first case gives only slightly less power transfer at low frequencies than the matched impedance load, but the frequency characteristic is more uniform because the "–3 db point" is more than doubled in frequency. Also the overall efficiency is improved, as deduced from Fig. 1. When the load resistance equals 2.8 R_G there is about 1 db loss from maximum at low frequencies, but a still more uniform frequency characteristic since the "–3 db point" is at about $f/f_o = 3$. Probably in most cases this load would be the better compromise. Both of these curves also eventually reach a slope of –6 db per octave. It can be seen that the resistance load, although not a matched load, is certainly an optimum in the usual case where uniform frequency response over a wide range is wanted.

Condition "C" represents that of a conjugate load, which is another way of saying that the generator reactance is tuned by the load reactance. This is the condition which the "Dictionary of Physics and Electronics" calls a matched impedance. At the resonance frequency f_o, conditions are the same as for Fig. 1 and the load receives 0.25 watt. At higher and lower frequencies the delivered power falls rapidly, again approaching the slope –6 db per octave. Under certain conditions a tuned circuit is desired, but in general, this would not be the optimum coupling condition in audio frequency circuits.

BRIDGING TYPE INTERCONNECTIONS

In the audio frequency range the vacuum tube amplifier presents a very high input impedance, and supplies an output impedance which can be made substantially anything desired. Since the amplifier supplies the power it is no longer necessary to draw maximum power from a signal generator circuit. The generator merely must supply a control voltage to the amplifier input. This leads to a very common type of circuit chain which is called the "bridging type interconnection" in this paper.

Curve 6 of Fig. 1 demonstrates that the voltage across the load is 0.91 of the generated voltage when the load resistance is ten times the generator resistance. In other words, for any load resistance greater than ten times the generator resistance there will be less than 1 db loss in generated voltage. Reference to the curve of total power delivered indicates that this type of connection makes small demands upon the driving circuit and in particular results in very small power losses in the generator. Consequently such circuits are extremely useful whenever reflections can be neglected, and they represent the bulk of the present-day audio frequency technology.

Figure 3 illustrates several conditions where this principle is used to advantage. Condition "B" shows a generator, which might be a moving coil microphone, under conditions of open circuit termination at left and matched termination at the right. It is seen that the full generated voltage would be furnished to the amplifier under the former conditions, whereas only one-half this voltage would be available with matched termination. It has been shown in another paper[1] that this causes a loss in signal-to-noise ratio of 3 db as well as the indicated loss in signal level of 6 db.

Condition "C" indicates a generator with a reactive impedance terminated in an amplifier with a grid resistor high compared with the generator reactance at all frequencies in the range of interest. Under these conditions the frequency variations in generator impedance will have negligible effect upon the amplifier output because substantially the full generated voltage is always applied to the grid. A good example is a reproducing head in a magnetic tape reproducer. Another is the Rochelle salt microphone or phonograph pickup which has capacitive reactance. In this case, moreover, the capacitance changes by a factor of more than 10 to 1 in the ordinary room temperature range, so that without the bridging type of interconnection very large changes in output would take place during normal use.

Condition "D" illustrates a generator of low internal resistance, with several high impedance loads connected to it. This is representative of a modern feedback amplifier driving loudspeakers in a "70-volt line" system. The feedback produces a low generator resistance, and across the output

many load resistances of fairly high value can be connected, all receiving nearly the amplifier-generated output voltage. Consequently the output of each loudspeaker will be practically constant regardless of the number of loudspeakers connected, up to the total power output capacity of the amplifier.

This, of course, is exactly the system used in electric power systems, in which the line voltage is maintained as nearly constant as possible and the impedance looking back into the lines is made very low. The generators give high efficiency because, from the maximum power standpoint, they are greatly underloaded. They are designed with conductors which reach maximum safe temperatures at the normal power levels and full capabilities of the driving turbines, and if they were loaded with matched impedance they would quickly burn up.

This type of connection accounts for the great popularity of cathode-followers. The gain of the tube is traded for an impedance transformation. It is possible to secure a low output impedance and a generated voltage essentially equal to the output voltage of the final high-impedance amplifier tube, with a device much cheaper than an output transformer, and with wide frequency range. This makes it possible to cascade units, or connect multiple loads, without paying much attention to impedance relationships except to maintain a "bridging ratio" of impedance *at all frequencies*—say a ratio of at least 10.

Condition "A" of Fig. 3 represents the bridging impedance concept in reverse—here the generator resistance is made much higher than the parallel resistance of the tuned circuit at resonance to maintain the maximum tuning sharpness for e_{out}. This means that substantially constant current flows, and e_{out} is essentially proportional to the full impedance change. If the tuned circuit resistance approached R_G at resonance the current would fall and the peak would be reduced. It is true that e_{out} is only a fraction of the generated voltage; however, if the generator is a pentode tube very substantial net amplifications result, as in the r-f and i-f sections of radio receivers.

OUTPUT STAGES

It originally was the practice to terminate an output amplifier in a resistance as nearly equal to the internal amplifier resistance as possible, because this would give maximum power transfer and minimum reflection losses. However it was soon realized that the criterion for an amplifier which is producing audio frequency signals is not the maximum obtainable power output, but is the maximum power for an acceptable amount of distortion. A vacuum tube characteristic is not linear, and the effects of its nonlinearity become smaller as the load resistance becomes greater. Consequently the optimum load turns out to be

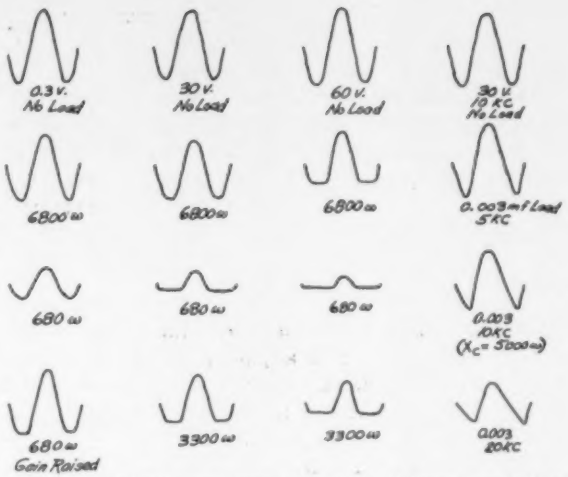

FIG. 4. Output wave forms of cathode follower, one-half of 12AU7, 200-volt supply, 50,000-ohm cathode resistor. Voltages peak-to-peak. Columns 1, 2, 3 at 1 kc. Small-signal generator resistance approximately 1,000 ohms.

considerably higher than a matched impedance, and in the pre-feedback days a load resistance of about 2.8 times the tube plate resistance gave the best performance. Now, of course, inverse feedback is used to straighten the curve, give a low generator output impedance and good regulation. It is most important, however, to realize that inverse feedback does not make the tube a bigger powerhouse. The tube continues to draw grid current, and continues to go to zero plate current at negative grid cutoff, at the same grid voltages as before. The feedback does increase the power output for a given distortion between these limits. Within its power capabilities it acts like a generator capable of supplying enormous power, but the maximum power it can deliver to a load circuit is not greatly altered by the use of feedback.

To illustrate this effect, Fig. 4 gives a number of tracings from a *CR* tube face of the output voltage of a cathode follower amplifier of typical design. This is one-half of a 12AU7 tube operating with 200 volts supply and 50,000 ohm cathode resistor. At 0.3 volt (all values peak-to-peak) output, it required a load of about 10,000 ohms resistance to reduce the voltage to 0.91 of the open-circuit value, indicating an internal resistance of about 1,000 ohms.

The curves of the first 3 columns were at 1 kc and in each column the grid drive was constant, top to bottom. The top row shows a fair wave form even at 60 volts output for no load. The second row shows little distortion at 0.3 volt, but bad distortion at 60 volts, for 6800 ohms load. A load of 680 ohms, somewhat below a match, while causing high distortion at higher voltages, may appear

satisfactory at 0.3 volt; but the bottom picture of column 1, made with raised oscilloscope amplification, shows flattened bottoms in the wave form even here.

The last column shows that the wave form remains good at 10 kc for no load. However, a capacitive load not causing much loss of amplification gives serious distortion as shown by the sharpening of the bottoms in the other examples of this column. This can occur if long cables are used with cathode followers.

CONCLUSION

The discussion has been concerned with ordinary circuit elements and vacuum tube amplifiers, but the same principles will apply to transistor circuits and negative-element circuit components although the application will not be so straightforward to most engineers.

In the colloquial sense of the matched set of golf clubs, the couple who form a perfect match, or the matching saddle and riding boots, hi-fi outfits will continue to be sold with matched components. It has been shown, however, that in engineering language the impedance relations coupling these components are more often not matched according to official definitions, but are optimized in various ways. In fact, for specific assemblages of equipment it is sometimes possible to make the impedance conditions give useful circuit equalization. Therefore it is urged that circuit designers, at least, think always in terms of optimum impedance, using the impedance condition that gives the best over-all result.

THE AUTHOR

William Boring Snow was born in San Francisco, California. He received the degree of A.B. in 1923 and the E.E. degree from Stanford University in 1925.

He was associated with the Bell Telephone Laboratories, Inc. from 1925 to 1941, where he pioneered in the development of stereophonic recording and special applications of magnetic recording. From 1941 to 1945 he was assistant director of the underseas warfare development project at the Columbia University Division of War Research. Mr. Snow joined the staff of the Vitro Corporation of America in 1946 and worked on various projects concerned with nuclear-energy instrumentation and underwater ordnance, among other things. He subsequently became Director of Physical Research and Development of that company.

In November 1952, Mr. Snow moved to Santa Monica, California, and established a consulting practice in acoustics and electronics. He is a Member of the AIEE, the IRE, the SMPTE, the APS, and the Acoustical Society of America. He holds five patents on stereophonic reproduction and recording. Throughout his career, Mr. Snow has published numerous papers.

Innovations in Studio Design and Construction in the Capitol Tower Recording Studios*

JAMES W. BAYLESS†
Capitol Records, Inc., Hollywood, California

Designed from the ground up for optimum electrical, mechanical, and acoustical characteristics for the production of recordings, the Capitol studios in Hollywood represent many advances in studio design. The objectives in planning the studios, and the methods used to achieve the objectives, are described.

INTRODUCTION

IN FEBRUARY of 1956, Capitol Records reached a long planned-for goal when West Coast operations were consolidated in a new combined studio and office building in Hollywood. The building (Fig. 1) is unique in a number of ways. It has already become a Hollywood landmark as it is the world's first office building in the form of a round tower.

Now widely known as the "Capitol Tower", the building was designed by Welton Becket, noted architect, and is a modern, striking, earthquake-resistant reinforced-concrete structure. It is 13 stories tall and 150′ high, the maximum building height permitted in Los Angeles.

The decor is in keeping with the outward appearance of the building. The ground floor, the only rectangular part of the building, is actually a separate structure which surrounds the tower and was joined to it after the entire tower was completed. It houses the Recording Department offices, tape-to-disk dubbing rooms, and three recording studios which were designed to be as modern and striking as the building itself.

Preparatory to planning the actual construction of the recording studios, comprehensive analysis of modern popular and classical recordings released during the past four years was undertaken. We attempted to evaluate the recording trends and characteristics that should be considered in the design of ideal recording facilities. The conclusion reached was that no conventional enclosure would be sufficiently versatile to embody all desirable features. We decided that we would have to utilize new principles to achieve a degree of versatility and control previously unavailable. The interdependence of the physical, acoustical and electromechanical requirements of a sound recording facility is so pronounced that the three are almost inseparable. Moreover, we felt that it was virtually impossible to achieve optimum results by the remodeling or the redesign of an existing structure, as was so often attempted in the past. In addition, we decided that a studio today must anticipate the requirements for production of binaural or multi-channel tapes and disks.

OBJECTIVES

Therefore, our major objectives in planning the studio were these:

(1) Physically, we wanted the studios to be as spacious as possible, within the limitations of area available; we wanted the studios to be very attractive in appearance, to be well illuminated, to provide good visibility and easy access between each studio and its control room, and to be conveniently accessible to the musicians and their instruments.

(2) Acoustically, we wanted the studios to have very low noise level; to have known, uniform, controllable reflective and absorptive characteristics; to have completely controllable reverberation characteristics, and to produce effective diffusion of sound so that microphone placement would not be critical.

(3) Electromechanically, we were interested in reliability, simplicity and versatility of equipment; convenience of maintenance; and ease of operation.

Mr. Michael Rettinger, the well-known authority on sound recording studio acoustics, and Mr. Edward Uecke, our Chief Electronics Engineer, were furnished with these specifications, and our new facilities are the result of their response. We feel that we have been gratifyingly successful in achieving all of our objectives.

* Paper delivered at the Eighth Annual Convention of the Audio Engineering Society, New York, September 26, 1956.
† Vice President, Manufacturing and Engineering.

FIG. 1. The Capitol Tower. Exterior view of Capitol Records' Studio and Office Building. The Recording Studios are located in the rectangular ground floor.

STUDIO CONSTRUCTION

The basic physical plant consists of three studios, two large (A & B), and one small, (C). Studio A is shown in Fig. 2. There are four reverberation chambers, all identical, built underground for sound isolation on the lot adjoining the building.

TABLE I. Studio Dimensions.

Studio	Dimensions	Volume	L : W : H ratios
A	62′ × 46′ × 20′	57 000 cu. ft.	3.1 : 2.3 : 1.0
B	62′ × 38′ × 20′	47 000	3.1 : 1.9 : 1.0
C	26′ × 15′ × 16′	6 200	1.6 : 0.9 : 1.0

The studio dimensions shown in Table I result in a favorable "floor area-to-total volume" ratio. The "length:width:height" ratios are non-integral to avoid pronounced room resonances.

The control booths are situated in corners to give maximum visibility and to minimize the floor area required.

Generous use of wood in the studio interiors was decided upon, for a number of reasons. It is known that musicians prefer wooden panelling in a room because wood is a uniform sound reinforcing material. Because of its lack of homogeneity, wood has no pronounced resonant frequencies, nor selective absorptive or reflective properties. Also, it was felt that the attractive surroundings resulting from its use would be conducive to the proper mood for outstanding performances by our artists. Therefore the doors, wall splays, ceiling splays and other appointments are all of natural finish hardwoods.

For uniform, bright, cheerful interior lighting we decided that, cost notwithstanding, there was no substitute for flush-mounted fluorescent fixtures. However, there is a potential noise problem involved in the use of fluorescent lighting because of ballast hum. This was avoided by mounting the ballasts remotely in an area outside the studios.

Low noise levels in the temperature and ventilation systems were effected by the use of decoupled ducts, sound traps and sound-proofed vents.

The floors are marked off into sections 13 by 13 tiles square. The center tile of each square is numbered. At every recording session the position of each musician, microphone, and wall splay is marked on a scale drawing of the studio containing a numbered grid which corresponds to the floor markings. We can then quickly duplicate any set-up by referring to the chart on file for the original session.

The acoustical design of the studios attenuates sound transmission between the studio and the external environment by 70 db. This results in an inherent noise level in the studios well below the usual "30 db above the threshold of audibility" criterion. This is also well below the thermal noise levels of the microphones and preamplifiers.

Our location at Hollywood and Vine requires measures

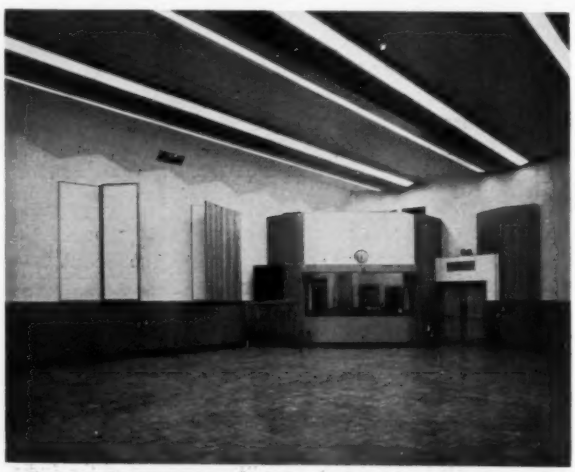

FIG. 2. Recording Studio A. Interior view showing control booth, wall and ceiling splays, and fluorescent lighting.

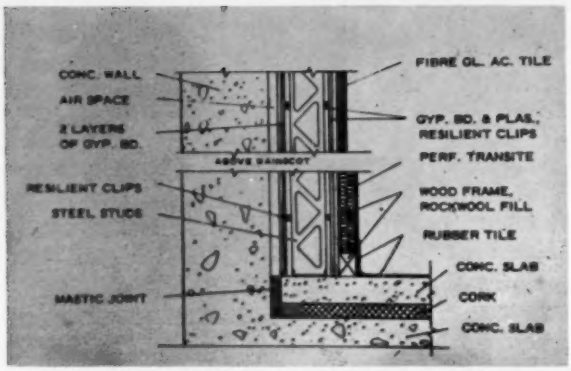

FIG. 3. Detail of studio wall, showing floating floor construction which isolates the wall from the concrete exterior.

to protect the studios against both air-borne and solid-borne noises. To produce the indicated sound isolation, the outer studio walls (Fig. 3) were constructed of concrete 10″ thick. A one-inch air-gap separates the outer wall from an inner stud wall. Acoustical components are fastened to, but mechanically decoupled from, the steel studs by specially designed resilient clips. The inner walls above the wainscot are finished with fibre-board covered with fibre-glass acoustical tile. The wainscot consists of a rockwool fill in a wood frame, finished with perforated transite. The inner wall stands on a floor which floats on a rubber tiled 3-inch concrete slab. This upper slab floats on a layer of cork which rests on the 6-inch concrete foundation slab. The cork and the upper slab are decoupled from the outer wall by a mastic joint.

The ceilings (Fig. 4) are suspended from the roof by wire hangers and runner angles, to which furring angles are wire-tied. The large air space between the room and the ceiling is filled with rockwool insulation. The acoustic material is fastened to the furring angles with resilient clips. Each studio is therefore actually a room within a room and is mechanically decoupled from the rest of the structure.

The control room windows are non-parallel double panes set in acoustical material, with silica-gel crystals between the panes for absorption of moisture. Acoustical safety doors 3″ thick are used throughout. These doors are laminated of nine layers of material including plywood, steel sheeting, rockwool, Goodrich vibration insulators and lead sheeting. The edges are trimmed with plastic foam strips, covered with fibre-glass cloth.

The wall splays and ceiling splays are angled at 15°. The elimination of large parallel surfaces tends to diffuse the sound and prevents echoes, dead-spots and unwanted interference or reinforcement patterns. Each wall splay (Fig. 5) in Studios A and B consists of two 10′ × 3½′ birch-veneered plywood panels 2½″ thick. The splays are adjustable so that they can either be "hard" or "soft". The soft side is covered with acoustic tile and is relatively non-reflective.

REVERBERATION CONTROL

The total reverberation time for each studio can be con-

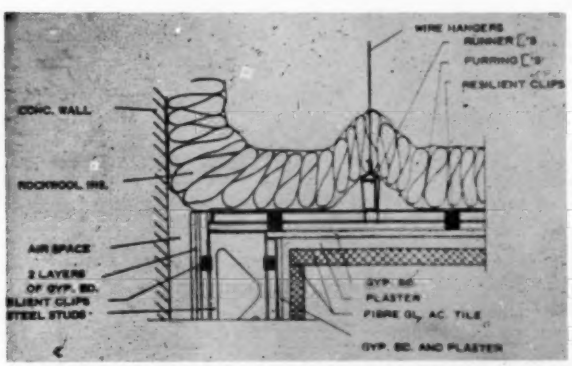

FIG. 4. Suspended ceiling construction in each studio. Wire hangers from the roof are tied to runners which support the ceiling by means of resilient clips.

FIG. 5. Closeup of studio wall. The "hard" and "soft" aspects of the adjustable wall splays are shown. The irregular geometry of the wall is clearly visible.

TABLE II. Studio Reverberation Times.

Studio	Volume	Reverberation time	
		Splays "hard"	Splays "soft"
A	57 000 cu. ft.	1.00 sec.	0.74 sec.
B	47 000	0.80	0.55
C	6 200	0.71	0.46

trolled by the positions of the splays, as shown in Table II.

The concept used in planning these studios was that of controlled, variable acoustics to permit recording a wide variety of music. Since reverberation can be added but not removed, the studios were designed for a minimum natural reverberation time. By selecting a shorter reverberation time than conventional studios of the same volume and area, we have found it possible to record a larger number of musicians in the same amount of space. The main advantage of the short reverberation time, however, is the flexibility it affords. Modern practice requires constant changes in the balance of sound; the studios are used for recording diverse types of music, and the amount of reverberation required varies from session to session. The studios are nearly uniform with respect to frequency; a slight rise of 30% at 100 cycles was deliberately introduced to conform with conventional room acoustics.

The short reverberation time and uniform absorption characteristics, together with the absence of pronounced resonances, combine to produce a high degree of clarity, intelligibility and separation. The recordings which result are characterized by an extremely clean musical response, with a great deal of "presence." This is particularly noticeable in the recording of string bass, high-level brasses or large choral groups. The producer and mixer find in these properties a greater versatility due to non-critical microphone and musician placement and complete control of the components of reverberation to be added. We have found it possible, for example, using a single mike pick-up, with sweeteners only, for a fairly large orchestra, to achieve separation comparable with a multi-mike technique in the past. The low leakage on a multi-mike set-up means no isolation is necessary between musicians and the vocalist. Because of the low reverberation time, very high levels of brass can be recorded with complete control and without sacrifice of "closeness," by placing the musicians farther away from the mike. Also important for the future is the fact that these same characteristics particularly lend themselves to the effective use of binaural or multi-channel recording techniques.

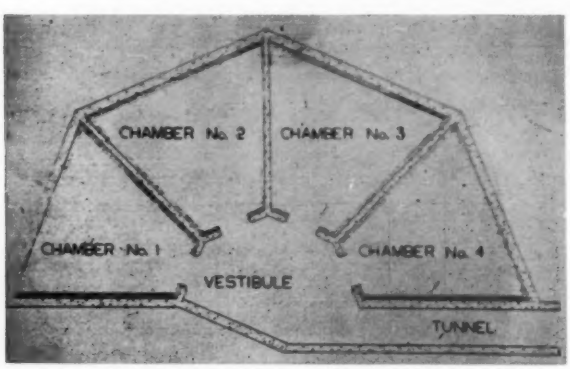

FIG. 6. Plan of reverberation chambers.

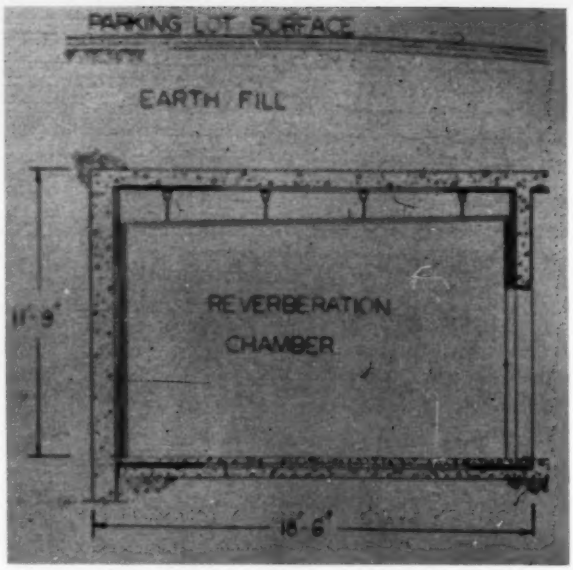

FIG. 7. Cross section of a reverberation chamber, showing its floating construction and sloped ceiling.

THE REVERBERATION CHAMBERS

In the past, it has been common practice for sound recording studios to utilize spare rooms, corridors or other available spaces as "echo" chambers, usually with insufficient regard to their reverberation characteristics. In most such cases, an undesirable sound-decay curve was inevitable. Close control of reverberation is the most important single factor in satisfactory recording acoustics. Such control could be achieved here because compatible reverberation chambers could be simultaneously designed to complement the studios.

We built four identical trapezoidal chambers with sloping ceilings, so that no parallel surfaces existed, (Fig. 6). This was done to prevent the occurrence of echoes or flutter. The chambers were placed underground for greater sound isolation and were constructed of reinforced concrete.[1]

[1] *Cf.* M. Rettinger, *J. Audio Eng. Soc.*, **5**, 18 (1957) and this issue.

The ceilings are suspended, furred and sound-proofed (Fig. 7); the inner floors float on cork over the bottom concrete floors; the adjacent double concrete walls are all sound-proofed for isolation and the interiors are surfaced with 2 layers of ¾"-thick metal lath and cement plaster.

Such acoustical treatment produces a uniform, non-discriminatory frequency characteristic. The chambers are approximately 2000 cu. ft. in volume and can provide a maximum reverberation period of 5 sec, although a 2.5 sec period is generally used. They display a relatively smooth sound decay curve that is approximately logarithmic with time, and a completely natural room tone can be obtained. As an experiment we have recorded the same 3-piece instrumental group in all three studios and have been able to achieve the same quality in each. The complementary design of studio and reverberation chamber thus permits the selection of optimal acoustics and room tone for each individual session.

ELECTROMECHANIC DESIGN

So that these facilities could be properly used, the associated electromechanical equipment was designed for extreme flexibility and a high degree of control.

A ten-channel mixing console permits the use of greatly varied and diverse mike set-ups (Fig. 8). A continuously controllable portion of the signal from any one or from any combination up to eight of these channels can be patched through the reverberation chamber. We often use a variable high-pass filter in the send line, set between 100 and 250 cycles, to prevent over-diffusion. The amplitude of the signal returning from the chamber can be continuously controlled.

FIG. 8. Control booth interior. The 10-channel mixing console appears in the center, the remote control panel for tape-machine operation adjacent to it, and the equipment racks in the rear.

FIG. 9. View of control booth from the rear, showing tape machines.

Another consideration in the electro-mechanical design of studios is the minimizing of unproductive delays during recording sessions. Non-critical placement of mike and musician was one step in this direction. In addition, we have located a remote control panel for operation of the tape machines adjacent to the mix console, and the equipment racks are located so that all operating controls are convenient to the seated engineer, (Fig. 9). An access room was constructed behind the racks, complete with ventilating system, to make maintenance and servicing easy. The flexibility of the equipment, together with routine preventive maintenance procedures, minimizes the possibility of session-time loss due to equipment failure.

With the consent of the telephone company we have also installed an automatic phone-disconnect relay actuated by the recording light switch. When the recording light is on, incoming calls receive a busy signal so that it is not necessary to take these calls in the studio.

The studios are provided with Altec 820 theatre sound systems consisting of two 15" woofers and a multi-cellular high frequency unit mounted in a furniture-style enclosure. The appearance and sound quality of this system is in keeping with the general atmosphere in evidence throughout the studios.

CONCLUSION

We at Capitol have had a unique opportunity: a chance to start from the ground up and create a recording facility embodying many features which modern recording practice makes desirable. We borrowed the techniques of motion picture sound-stage design and construction to achieve low noise levels and proper diffusion. We employed modern

advances in acoustical materials and constructions to achieve a new concept in studio design: minimized reverberation, but a nearly flat characteristic. We designed compatible reverberation chambers to provide optimal acoustical properties. The result has been a modern, diversified plant, physically attractive, acoustically controllable and electromechanically flexible. This combination provides the fulfillment of the esthetic considerations important to the artist and the practical engineering considerations of concern to the producer.

JOURNAL OF THE AUDIO ENGINEERING SOCIETY APRIL 1957, VOLUME 5, NUMBER 2

The Bias Characteristics of Tape Recorders*

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This paper discusses the problem of setting operating bias current so that the ultimate in performance can be obtained from "Long Recording" type tapes, which possess more critical bias-output characteristics than do the standard varieties. The results of a wide survey of commercial-recorder bias are given, and it is concluded that machines should be equipped with provision for bias adjustment.

INTRODUCTION

THE SUBJECT of effective bias current and its relation to the performance of magnetic tape has been discussed for several years to help the industry realize more of the ultimate in recorder performance. New types of tape have been placed on the market every year or so, which have affected the relationship between tape and recorder. The purpose of this paper is to acquaint industry with some of the characteristics of today's tapes and to present some statistics concerning effective bias current on commercial recorders.

METHOD OF DETERMINING EFFECTIVE BIAS

The method used to determine the effective bias current of each particular recorder utilizes a so-called Bias-Setting tape.[1] This tape is composed of two sections differing greatly from one another in coercive force. The bias *vs.* output characteristics of the two sections of tape are shown in Fig. 1. The data for these curves were taken on a Standard Reference Recorder at a speed of 7.5 ips, using a frequency of 1 kc and a recording level 20 db below that corresponding to 3% harmonic distortion at the peak bias of the section labeled tape #2. Because of the great difference in the shape of the two curves, a fairly accurate determination of effective bias current is possible. For example, the Bias-Setting tape is recorded with 1-kc tone at 7.5 ips with proper level on the recorder under study, and on playback it is observed that tape #1 has 2 db greater

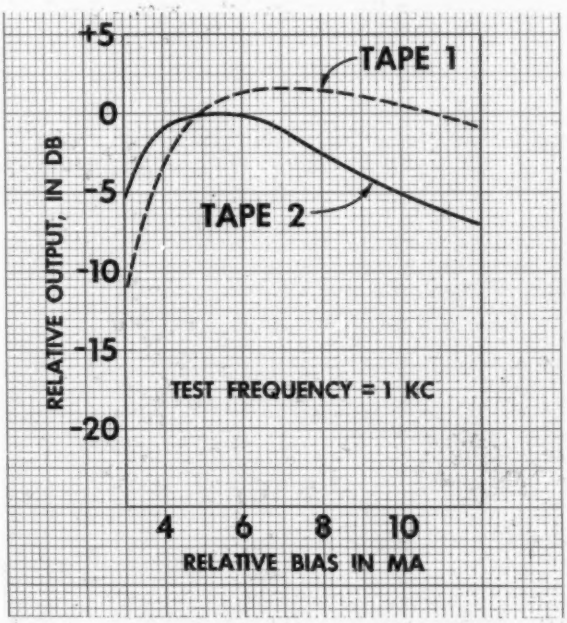

FIG. 1. Bias *vs* output curves for BIAS-SETTING tapes.

* Paper delivered at the Seventh Annual Convention of the Audio Engineering Society, New York, October 13, 1955. Revised manuscript received November 8, 1957.

[1] C. J. LeBel, *Audio Record*, 5, No. 6 (1949).

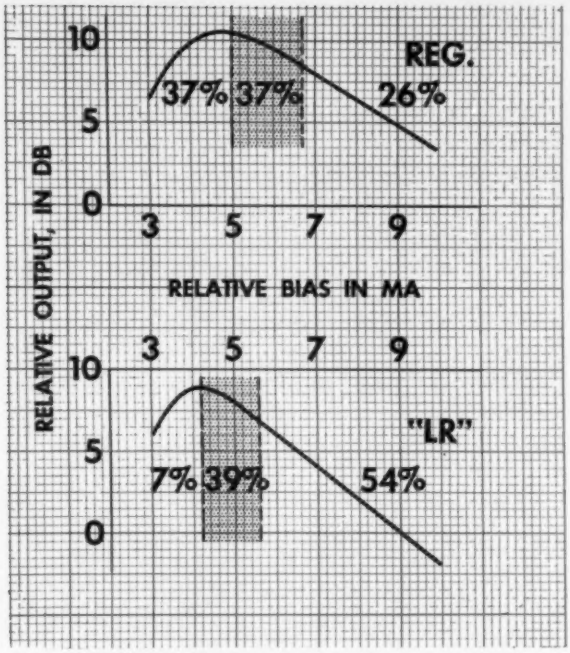

FIG. 2. Percentage distribution of 57 tape machines when their effective bias currents are plotted upon the bias-output curves of "Regular" (top) and "LR" (bottom) tapes at 1 kc.

output than tape #2. The bias current giving a difference of 2 db on the two curves of Fig. 1 is found to be the equivalent of 7 ma of bias current on the Standard Reference Recorder. In this way it was possible to measure the effective bias current for each recorder during the survey, and thus to plot the distribution of values.

TESTS OF COMMERCIAL MACHINES

Fifty-seven tape recorders, representing nineteen manufacturers, were studied. The list prices ranged from $140 to $2000. In all cases the bias current had been set at the manufacturer's plant, or by authorized field personnel in accordance with manufacturer's instructions.

Prior to the study of each machine, the two curves shown in Fig. 2 were obtained by running two types of tape, "Regular" (top) and "LR" (bottom), on the Standard Reference Recorder at 7½ ips tape speed, a frequency of 1 kc, and at a level 20 db below 3% total distortion at the peak bias of each tape. These curves show the dependence of the output level upon the bias setting.

Using the method described in the preceding section, the output of each machine for the two types of tape was then determined, and plotted on the respective graph of Fig. 2 against its corresponding effective bias current.

Results with "Regular" Tape

The upper section of Fig. 2 shows the resulting distribution for a "Regular" tape. The shaded area represents a range of bias current, from that corresponding to peak output to where the output drops 2 db. Surprisingly only 37 per cent of the recorders tested fell within this area; 26 per cent were over-biased and 37 per cent were under-biased. Under-biasing is particularly undesirable, since distortion increases rapidly below peak output. In fact, a reduction in bias current which will reduce output by only 1 db from peak results in a loss of approximately 5 db in signal-to-noise ratio (for a given maximum distortion).

Results with LR Tape

The lower section of Fig. 2 represents the distribution of Recorder settings plotted against the curve of an "LR" type tape made on the Standard Reference Recorder. In order to increase footage on a standard 7" reel by 50%, "LR" tape is reduced in coating thickness. This gives a sharper, more critical bias current range: only 60% of that obtained on a regular tape. On such tape, 54% of the recorders tested were over-biased, 39% were within the desired range, and 7% were under-biased. Over-biasing, unless extreme, does not appreciably reduce signal-to-noise ratio; however, the high-frequency response of the tape is affected adversely, as is now shown.

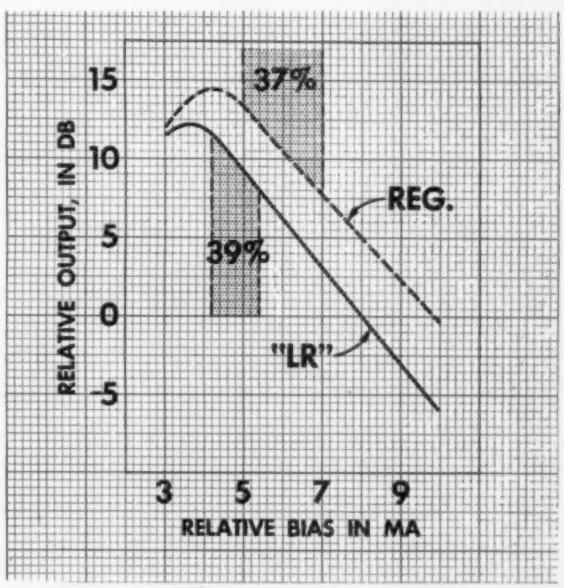

FIG. 3. The same percentages shown in Fig. 2 when plotted upon the bias-output curves taken at 7.5 kc cover a wider output range. The high-frequency loss which results from over-biasing is clearly evident.

Figure 3 shows the same distribution of effective bias current plotted against the bias-output curves of the same tapes shown in Fig. 2, using a frequency of 7.5 kc. The rapid loss at 7.5 kc as the effective bias is increased is quite obvious. At 9 ma of bias current the 7.5-kc output falls 15 db below peak output.

PRE-EMPHASIS LIMITATION

The high-frequency loss due to over-biasing can be compensated for by using more high frequency pre-emphasis during recording. However, there is a very definite limit to the amount of pre-emphasis which may be used, due to saturation overload effects; this is particularly serious in machines which offer a frequency range of 1500 to 2000 cps per inch of tape speed.

CONCLUSION

From these tests one may conclude that it is not sufficient to use the customary procedure of setting the bias to the same current value in all machines, due to variations in head characteristics.

The manufacturers who provide a means for bias current adjustment on their recorders have no problem if their bias metering arrangements are disregarded, since the recordist can adjust for any tape. For the manufacturers of fixed-bias recorders, we suggest that a tape or a system of tapes be used to set effective bias current, in order to achieve optimum machine performance. In view of the serious effect of excessive bias on high frequency response, this procedure is obviously essential.

The Application of Velocity Microphones to Stereophonic Recording*

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Some observations on the stereophonic effect using one channel (pseudo-stereophony) and two channels are presented. Since microphone characteristics play an essential role in stereophonic transmission, the use of velocity microphones in this connection is considered, and the constructional features of a recent type briefly described.

SINGLE VS. DUAL CHANNEL REPRODUCTION

IT IS GENERALLY agreed that reproduction with two channels is an improvement over one. Fletcher and his colleagues have investigated this question thoroughly. A piece of music was played to a group of musicians, through a single channel with linear frequency curve up to 15,000 cps, *i.e.*, full frequency range. At the same time, though alternately, the music was played through a 2-channel system. At the beginning of the experiment, the frequency response was the same for both systems of transmission, but gradually the high frequencies in the dual channel system were cut away. Yet the judges continued to point out the dual channel system as the better, even when the high frequencies in the dual system were cut right down to 5000 cps. Fletcher's experiment not only shows that 2-channel reproduction gives a material improvement in quality, but also, indirectly, tells us something about the perception of the high notes in reproduction through a dual channel system, compared with that from a single channel system. From my own experience I have found that a stereophonic recording seems more bassy when you listen to one sound track of a dual system, while, as soon as you add the other, you have the feeling that there is a greater frequency range. The introduction of FM broadcasting, and its spread over most of the globe; this system's greater freedom from noise, the possibility of achieving a greater range of frequency, and a less distorted reproduction of music, together with similar conditions for recording technique—all this has very much sharpened the popular appetite for high frequencies. It appears, however, that the presence of high frequencies in single channel reproduction is not always synonymous with high quality. It may be unfair to ridicule the bad taste of those who turn the tone-control to "bass". They may do so, not because they dislike the highs, but rather because the latter tones emanate from a comparatively tiny center of sound, which is consequently unpleasant to listen to. Various people have observed this, as is shown by the experiments in Germany with the so-called "Ball loudspeakers," and the extensive production of so-called "3-D" radios in Europe. The aim is to spread the high frequencies and reflect them from the walls of the room, so that one does not get the feeling that the high notes originate from a point source.

PSEUDO-STEREOPHONY

Perhaps the pleasant effect associated with stereophonic reproduction is due, first and foremost, to the feeling of a diffused sound source. I will mention two experiments that throw some light on this question. They aim to produce this feeling of a diffused source of sound, and also a stereophonic—or rather a pseudo-stereophonic—effect, from a single channel transmission. I have previously mentioned the German experiments with the "Ball loudspeaker." In the following, I shall use the term "sound picture" for lack of a better way to express the diffused and extended effect obtained in stereo-reproduction. These two experiments employ two loudspeakers, at a suitable distance apart. They are based on an interesting characteristic of human hearing, *i.e.*, that two separate sources of sound putting out the same sound picture, are not perceived as two but as one "synthetic" source. The location of this synthetic source between the two real sources depends upon the comparative strengths of the latter.

* Delivered at the Eighth Annual Convention of the Audio Engineering Society, New York, September 26, 1956. Revised manuscript received September 23, 1957.
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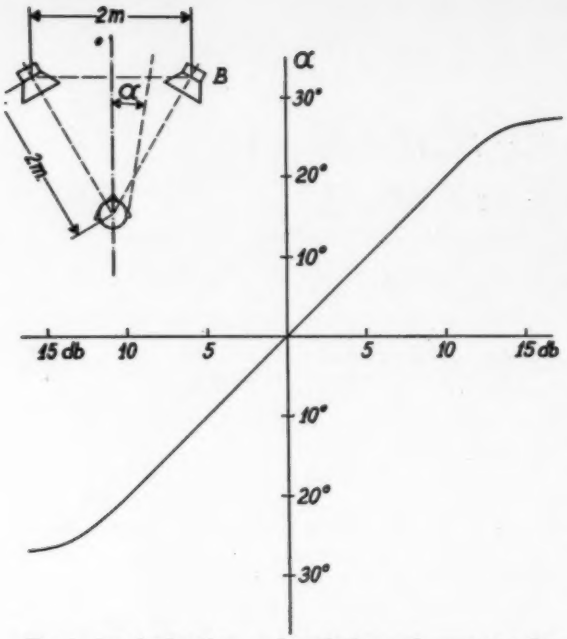

FIG. 1. Angular location, α, of synthetic sound source as a function of the level difference between loudspeakers A and B when arranged with respect to the observer as shown.

In Fig. 1, the two loudspeakers, *A* and *B*, are placed 2 meters apart. Two meters from the mid-point on the perpendicular to the axis between the two loudspeakers, is an observer. The curves show the angle of divergence for the synthetic sound source as a function of the difference in level between the two loudspeakers. It is clear that the proportionality factor depends on the distance of the observer from the loudspeakers. The curve shown here, averaged from several empirical curves employing various observers, results from a considerable investigation carried out by Dr. V. L. Jordan, of the Danish State Radio.

Simple Frequency Division

The first experiment simply divides a single channel transmission between two loudspeakers by means of a filter, in such a way that the sound spectrum, to the observer, is evenly spread over the space between the two loudspeakers (Fig. 2). In this example, sounds with a frequency of 800 cps will seem to come from a point midway between the two loudspeakers, lower frequencies from the left, and higher frequencies from the right. The result is a broad sound picture. The positioning of the sounds, of course, gives a false picture, but the combined effect is "stereophonic."

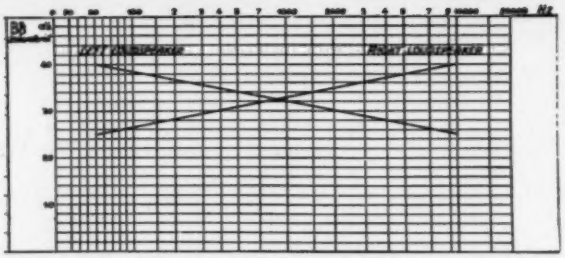

FIG. 2. Effect of simple frequency division (at 800 cps) upon relative levels of left- and right-loudspeakers.

The Lauridsen Effect

The second experiment gives a still more "stereophonic" impression. It is described by Mr. H. Lauridsen, an engineer with the Danish State Radio. It utilizes a tape recorder with two reproducing heads set in relation to each other in such a way that in listening to the two heads through their respective amplifiers, there is a time lag between them of 50 to 100 msec.

A single-track recording is now played, and the signal from the first recording head (which we will call the primary signal), is connected to two loudspeakers, *A* and *B*. These are placed at a suitable distance apart, with their cones in phase. At the same time, the signal from the second recording head, the delayed one, is also connected to the two loudspeakers, but such that this signal moves the two cones in opposite phase (see Fig. 3). The arrangement can be set up as shown in the diagram, Fig. 4, where *A* and *B* are the two loudspeakers, R_1, the primary signal, and R_2, the delayed signal. The phasing is changed in the one loudspeaker by means of the transformer *T*. If the primary signal is connected to the two loudspeakers, and

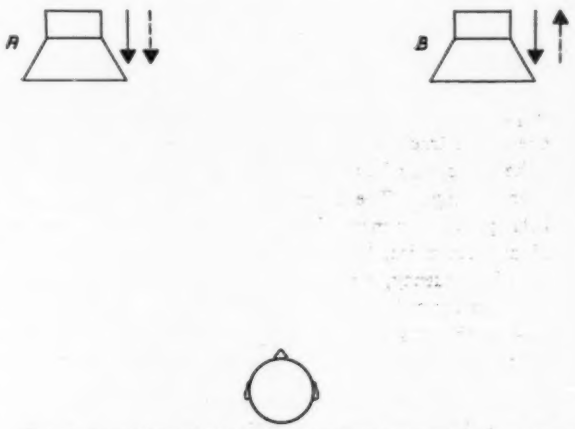

FIG. 3. Lauridsen method indicating in-phase excitation of loudspeaker A and out-of-phase excitation of loudspeaker B.

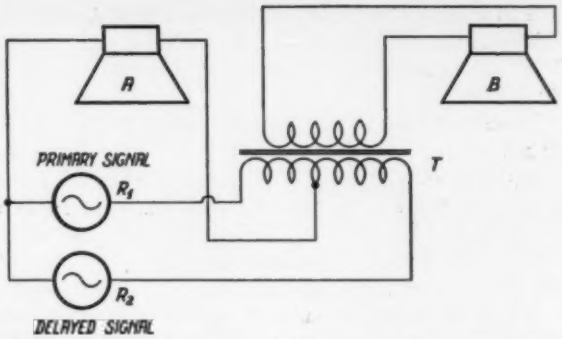

FIG. 4. Schematic diagram for demonstrating pseudo-stereophonic effect.

the delayed signal is slowly added, so that this is connected to the same phase on both loudspeakers, you get the impression of a recording that becomes indistinct because there is too much echo, and the entire sound appears to come from a point between the two loudspeakers. But if, then, without altering the level, you reverse the phase of one of the loudspeakers, for the delayed signal only, one gets a strong impression of space, and a feeling that there is a large and extensive sound source between the two loudspeakers.

The impression of space cannot be due entirely to the delay of the second signal, otherwise the same impression would be given when hearing the two signals in the same phase on the two loudspeakers. The effect of space arises because, by allowing the two loudspeakers A and B to work out of phase for the delayed signal, a difference in level on the two loudspeakers is obtained for the various frequencies, thereby producing different synthetic sound pictures between the two loudspeakers.

Unlike the first experiment, the whole sound spectrum is here spread out over the entire space between the loudspeakers A and B. The explanation for this is most easily understood from an example. (See Fig. 5.)

If, for instance, a signal of 100 cps is played and the delay is 50 msec, the delayed sound will be in phase with the primary sound. If the two signals are in phase on loudspeaker A, they will be out of phase on loudspeaker B; the synthetic sound-picture is at A. If the frequency is changed to 110 cps, the delayed signal will be precisely in opposite phase with the primary signal. That is to say, the two signals will be in phase on loudspeaker B, and out of phase on loudspeaker A. The synthetic sound picture will be at B. With signals between 100 and 110 cps, the two signals will be partly in, and partly out of phase at A and B, so that the synthetic sound picture lies between A and B, and these frequencies are distributed in this space. This distribution will be more effective, the higher the frequency.

These experiments work best when carried out in a comparatively dead room.

Anyone with the equipment can perform these experiments, and, in a direct comparison with a true stereophonic recording, will be astonished by the similarity in quality, especially in the second experiment. This similarity is particularly conspicuous with sounds such as applause, where precise localization of the sound is not expected.

I have described these experiments fully, in order to emphasize that the psychological factor—the ability to localize the sound outside the real source—is an important condition for our being able, all things considered, to achieve true auditory perspective in a listening room, and also to show that one of the most important factors in improving the quality of sound transmission is the creation of an extended sound source.

TRUE STEREOPHONY

If we now turn to true stereophonic reproduction, we find that here it is not only a question of giving the illusion of a diffuse source, but of placing the individual sources in their true locations. Many so-called "binaural" recordings suffer from the defect of a "hole" in the middle, between the two loudspeakers. It appears that the ribbon microphone is particularly suitable for achieving truthful acoustical perspective, using only two loudspeakers.

Let us look at Fig. 1, which shows the angle of divergence for the synthetic sound source as a function of the difference in level between the two loudspeakers. On the basis of this curve, it is possible to work out the theoretically correct directional characteristic for the two recording microphones, provided that the listener is situated on the axis perpendicular to, and midway between, the loudspeakers.

The condition is that the two microphones shall have

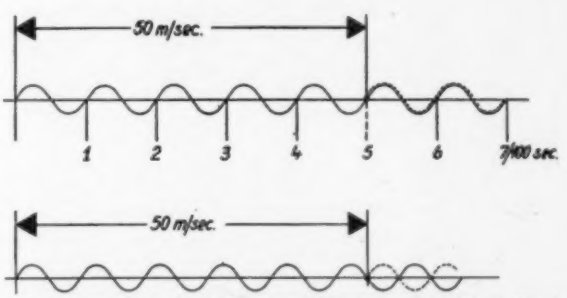

FIG. 5. If a 50 msec delay is applied to a 100 eps tone (top), both signals will be in phase at A and out of phase by 180° at B, thus locating the source at A. If the same delay is applied to a 110 eps tone (bottom), the situation will be reversed, and the source will seem to be at B. For frequencies in between, the source will seem to be somewhere on the axis AB.

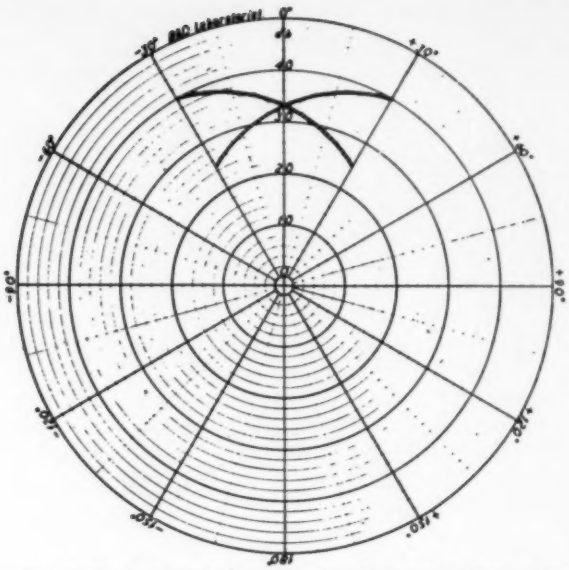

FIG. 6. Segments of two logarithmic spirals lying within a 60° recording angle (see text).

directional characteristics such that their sensitive volume in the recording studio increases in proportion to the angle made by the sound source with the axis of symmetry. Theoretically, this can be obtained if the characteristics of the two microphones are logarithmic spirals, running in opposite directions, with equal rates of increase.

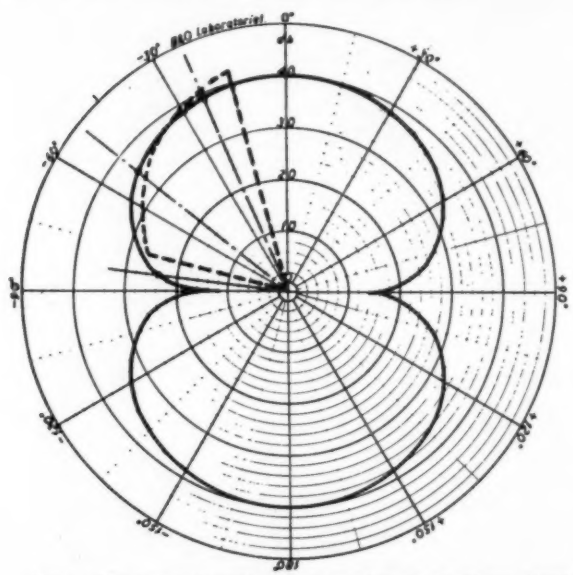

FIG. 7. The cosine characteristic of a velocity microphone closely approximates a segment of a logarithmic spiral.

This concerns the angle that is to be recorded. Outside this area, the sensitivity should, theoretically, be zero. In Fig. 6, these curves are drawn within a recording angle of 60 degrees.

If we now look at the directional characteristic of the ribbon microphone (solid curve, Fig. 7), we see that we have, very nearly, this sort of curve on part of the polar characteristic of the ribbon microphone—i.e., when the axis of the ribbon microphone is turned about 45 degrees to the center point of the orchestra, and when the outer points of the orchestra and the microphone form an isosceles triangle. In Fig. 7, this theoretical curve is superimposed as a dotted line on the directional characteristic of the ribbon microphone.

In Fig. 8, the two microphones are set up in front of an

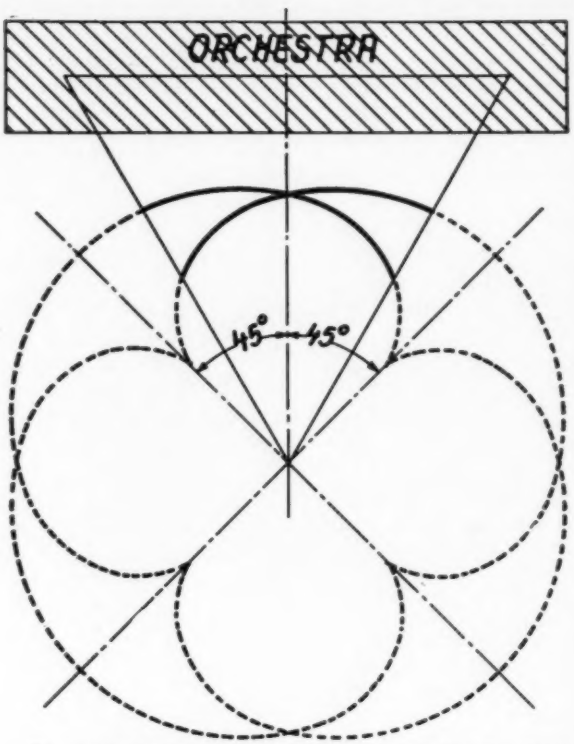

FIG. 8. Overall polar characteristic of two velocity microphones placed perpendicular to each other and at a 45° angle to the orchestra.

orchestra. The directional characteristics of the two microphones are given. The section of the curve used for the stereophonic recording is fully drawn, while the unused portions are dotted.

In our Laboratory, we have made a number of stereophonic tapes using this arrangement with two ribbon micro-

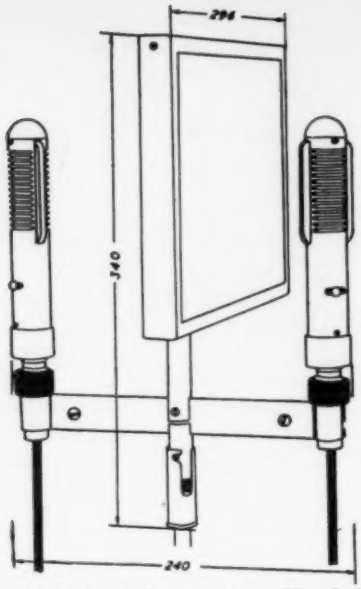

FIG. 9. Location of acoustic screen to avoid undesirable pickup from back lobe of microphone.

phones (B&O-50), to be described in the following section. Our experience shows that quite good stereophonic recording can be achieved. The best results are obtained when both recording and reproduction rooms are well damped. In the case of the recording room, this requirement is due to the fact that a large fraction of the microphones' acceptance range is not used in stereophonic recording. Hence if the surfaces of the recording room are too hard, the microphone will unavoidably pick up reverberations from the wall, and thus mask the stereophonic effect. We have tried using unidirectional microphones, but these proved not so suitable, since their directional characteristic is extremely dependent on the frequency. I consider, therefore, that the ribbon microphone, with a cosine (figure-eight) characteristic is more suitable, because its directional characteristic is less dependent on the frequency.

Unless one is extremely careful in setting up the microphones, there is the possibility of picking up sounds from the left side of the orchestra with the back response of the right-hand microphone. This, in reproduction, can be most confusing. To prevent this, we have produced an acoustic screen, which is set up between the microphones during recording (see Fig. 9).

DESCRIPTION OF MICROPHONE

The microphones employed in the experiments above are velocity microphones, B&O-50 and -53 which were designed to fill the need for a reasonably priced, good quality microphone with the following characteristics:

1. Linear frequency response over the audible range,
2. Minimal non-linear distortion,
3. Uniform polar pattern over as wide a frequency range as possible,
4. Adequate sensitivity for use with ordinary commercial tape recorders,
5. Adaptable for use with various makes of tape recorders,
6. The microphone should, in size and appearance, satisfy modern requirements in such microphones.

The pressure gradient, or velocity, type was chosen since, by the selection of the proper constants, the above requirements could most easily be met.

Table I presents the specifications met by this instrument.

TABLE I. Specifications at 1000 cps.

	Output Impedance		
	50 ohm	250 ohm	40,000 ohm
Open Circuit Output 0 db = 1v/μbar	– 80.7 db	– 67.1 db	– 56.1 db
RETMA Sensitivity, G_m (0 db = 1 mw at 0.0002 dynes/cm^2)	–138.7 db (38 ohms)	–128 db (150 ohms)	–129.1 db
RETMA Hum Sensitivity, G_H (0 db = 1 mw at 0.0002 oersted)	–139.8 db		

The polar response, (solid curve, Fig. 7), is uniform for frequencies from 100 to 10,000 cps.

The microphone (Fig. 10) is essentially a tube made of iron. The sound waves pass through horizontal slots in the

FIG. 10 (left). Assembled view of microphone.
FIG. 11 (right). Disassembled view of microphone.

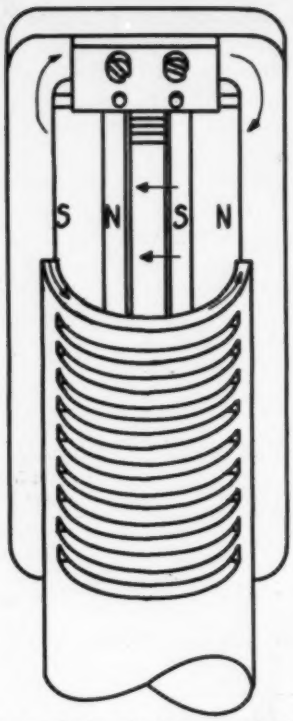

FIG. 12. Diagram of microphone interior showing ribbon, magnet assembly, and slotted tube.

tube to actuate the ribbon. The microphone unit itself is fitted into this tube in two vertical slits, so that the element forms a pair of wings on this tube.

In Fig. 11, the microphone element is shown disassembled, and the compact construction of the element is evident. The magnets themselves form the shoes of the poles, and the extremely concentrated magnetic circuit is shown in Fig. 12. The magnetic circuit is enclosed, since the rectangular iron frame, the sides of which form the two wings on the microphone, and the circular iron tube in which the element is mounted, guide the magnetic lines. By thus reducing the spread and leakage in the magnetic system, an extremely high field density is obtained. The magnets themselves are made of the anisotropic magnet material, Ticonal-E, and are magnetized in the direction of the arrow. The ribbon is stretched and directly attached at the top to the rectangular iron frame, while at the bottom, it is attached to a piece of insulating material. The current induced in the ribbon is taken off the microphone element at the bottom of the ribbon and at the rectangular iron frame. This arrangement has an advantage in that disturbing external magnetic fields induce currents in opposite directions which cancel out.

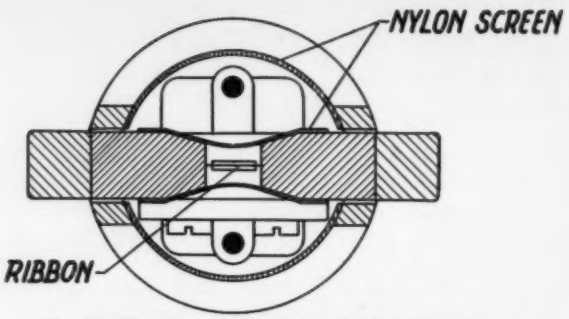

FIG. 13. Top view of microphone showing nylon screens.

To protect the ribbon against damage from wind and blast, a piece of nylon material is glued on both sides of the magnet. Besides this precaution, a nylon sleeve is also glued inside the iron tube (Fig. 13). These nylon screens serve also to damp the ribbon resonances.

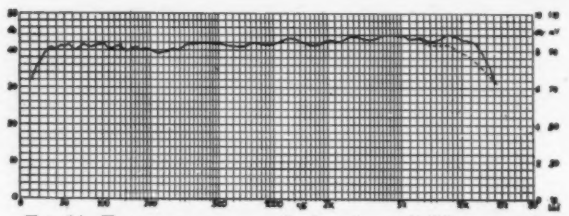

FIG. 14. Frequency response of microphone. Solid curve: microphone alone; dotted curve: microphone in slotted tube.

It is well known that the limit of the high frequency response of a ribbon microphone is set by the size of the baffle area around the ribbon. A linear response may, theoretically, be obtained up to a wavelength that is equal to the distance from the front to the back of the ribbon, or, what is the same thing, the width of the microphone.

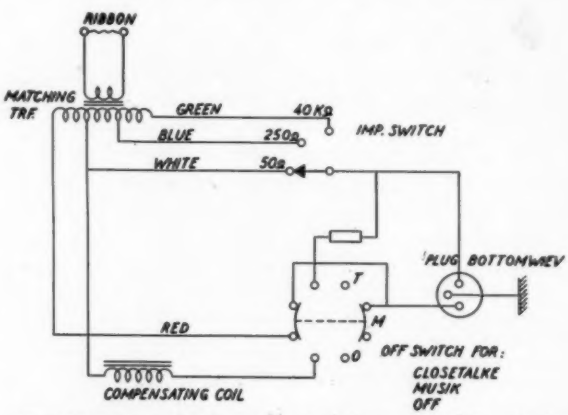

FIG. 15. Schematic diagram of microphone connections, showing impedance selector and frequency compensation.

For response up to 10 kc, the width of the microphone must not exceed about 34 mm. The width is actually 37 mm. In practice, a more extended response is obtained, due probably to the fact that the distance from the front to the back of the ribbon at the ends of the microphone is somewhat shorter. Further, it has been found, that the flatness of the frequency response curve extends further into the high frequencies when the microphone element, as here, is fitted into a tube. An exact theoretical investigation of this has not been made, but it is probably due to the resonances in the space between the ribbon and the circular tube.

In Fig. 14, the dotted curve shows the frequency response of the microphone measured alone, while the solid curve results when the microphone element is fitted into the circular tube.

As will be seen from Fig. 11, the necessary impedance-matching transformer is mounted directly on the microphone element so that loss in the leads from the element is kept to a minimum. The microphone is fitted either with single impedance output, usually 50 ohms, (the B&O-50) or, with 3 different impedances: 50 ohms, 250 ohms, and 40,000 ohms, (B&O-53). These are selected by turning the screw at the back of the microphone.

In front of the microphone there is a 3-position switch: Off, Music, and Speech. In the latter position, a choke is connected (Fig. 15) which drops the response at the rate of about 6 db/octave to compensate for the increase in the low frequency response close to the microphone.

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2. W. B. Snow, "Basic Principles of Stereophonic Sound", *IRE Trans. Audio*, AU-3, No. 3, March-April 1955.

3. V. L. Jordan, "Stereofonisk Transmission", *Ingeniøren*, No. 21, 1947.

4. H. Lauridsen, "Forsøg vedrørende rumakustisk gengivelse", *Ingeniøren*, No. 47, 1954.

An In-Line Two-Channel Magnetic Head of Universal Application*

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A newly designed two-track magnetic tape head is described, which has high crosstalk rejection between adjoining channels. This permits use of the design in a single head which may be used for full-track, half-track, and two-track stereophonic use. The basic design incorporates crosstalk rejection of 60 db in the mid-audio frequency range. Crosstalk rejection of this order makes—on a practical basis—inter-channel crosstalk as low as or lower than the signal-to-noise ratio in machines of professional quality. Short discussions and explanations are included on the causes of inter-channel crosstalk, including that from transformer action and that from magnetic fields about the tape itself. The head is simple to produce with reproducible characteristics from head to head and channel to channel.

INTRODUCTION

ONE OF THE outstanding developments in the high-fidelity industry, and an essential part of facsimile recreation of sound is stereophony—the use of two or more independent channels from recording microphone to reproducing loudspeaker—so that all of the depth and reality of the original performance are recreated. Snyder[1] and Snow[2] point out that in order to achieve facsimile reproduction, it is necessary that at least two channels be used and that this step is a major one toward the ultimate in realism. Increasing the number of channels from two to three does produce an audible improvement, but the practicality of popularizing such a system for the home is impeded by the greatly increased cost of such a step. Further studies and experiments by Snyder and Selsted[3] involving the San Francisco Symphony Orchestra and a succession of audiences containing trained musicians, audio engineers and lay individuals, showed that upon review of the tapes in a small auditorium of near ideal acoustics, three-channel material afforded negligible advantage over two-channel presentation of the same material. It is therefore concluded that a two-channel stereophonic presentation of program material is very desirable for the home field.

Magnetic tape offers a medium which at once provides a simple and elegant means of stereophonic recording and reproducing; the well known advantages of tape with respect to distortion, noise, dynamic range and frequency response, etc., need not be recounted, but by the same token tape provides a means for keeping the tracks in almost perfect register. From the technical point of view, the only disadvantage of stereophonic tape has been the problem of inter-channel isolation. The necessity for inter-channel isolation was recognized by early experimenters; in the magnetic recording field it was accomplished by the expedient of physically separating the heads for recording and reproducing the two channels. This system produced what is called in the trade a "staggered-head" stereo recording. Although the "staggered-head" system did solve the crosstalk problem simply, it created other and perhaps worse problems, because the tapes produced cannot be edited or spliced in the same silent manner as single-channel tapes. In addition, the staggered heads have two other disadvantages—in popular priced machines it is difficult to maintain the correct head spacing within tolerances required for realistic stereophony—and a compact machine is difficult to design because staggering requires space.

In order to avoid these problems, Ampex pioneered the development of stereophonic tape equipment with the heads and gaps one over the other or "in-line." The course chosen was not easy because it required solution of the problem of crosstalk between channels. Construction of two-channel

* Manuscript received September 18, 1956. Revised manuscript received December 9, 1957. Delivered at the Eighth Annual Meeting of the Audio Engineering Society, Septembr 26, 1956.

† Senior Engineer, Instrumentation Division.

[1] Ross H. Snyder, "History and Development of Stereophonic Sound Recording", *J. Audio Eng. Soc.*, Volume 1, No. 2, April 1953.

[2] W. B. Snow, "Basic Principles of Stereophonic Sound", *J. SMPTE*, 61, 567-587 (1953).

[3] Ross H. Snyder and Walter Selsted, "Acoustical and Electrical Considerations in Approaching Facsimile Reproduction of the Symphony Orchestra." Paper presented at Acoustical Society of America, Cambridge, Mass., 22 June 1956.

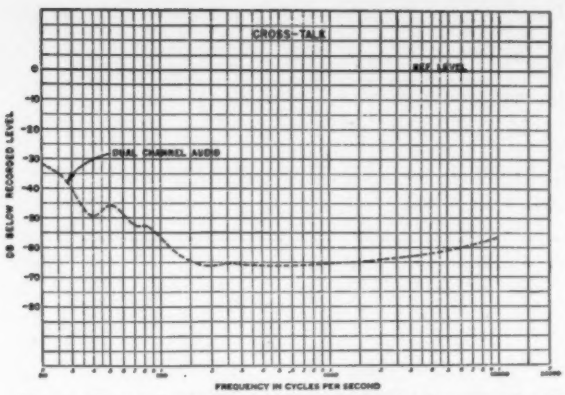

FIG. 1. Cross-talk characteristics of in-line head measured with near-saturated tape.

stereo heads up to the present time has been a compromise between crosstalk rejection and signal-to-noise ratio; with a given amount of tape width, the space devoted to inter-channel shielding was not available for track width, with consequent lower levels and reduced signal-to-noise ratio. The design adopted provided an isolation between channels of approximately 30 db, which as experience substantiated, proved to be adequate to preserve the stereophonic effect. The signal-to-noise ratio was only slightly reduced, but was acceptable in all but the most critical applications.

This head design, however, was not suited for general use in popular priced equipment, such as that for the home, because this head *cannot* be used for reproducing half-track material, particularly tapes having programs in both directions. If, as usually happens during a quiet passage in the desired program, there are heard at a 30-db lower level the weird sounds of a loud passage on the opposite track, and reproduced backwards in addition, the results will scarcely encourage the widespread use of a given product!

In the professional field, there are equally cogent reasons to encourage the development of a magnetic head of low inter-channel crosstalk. In making stereophonic master recordings, the professional recordists strive to obtain a maximum of inter-channel isolation, because crosstalk reduces the presence or realism of a recording. This effect is compounded in proportion to the generation or the number of times a copy is made from each other, so that the higher the isolation the better. In the production of heads for instrumentation recorders, there are requirements for a highly accurate (both mechanical and electrical) two-channel head for quarter-inch tape. Often data is compared one channel to another in real time. Again, a primary requirement is machine-to-machine reproducibility, so that tapes recorded on one machine in New York will be reproduced on another machine in Chicago with as nearly as possible identical characteristics. Thus the desirable characteristics of an instrumentation head apply equally to audio heads.

Figure 1 shows the electrical crosstalk characteristics of this head with tape that was recorded very near saturation. Near-saturated tape is obviously the worst condition under which to measure crosstalk, because the field directly adjacent to tracks tends to spread more than at normal levels. The curve was taken through doubly-tuned SKL filters so that the noise level would be dropped sufficiently to allow measurement of the crosstalk rejection. The rising characteristic of the curve at low frequencies is caused by geometrical or long wavelength coupling between channels. This effect diminishes as the wavelength diminishes, and at frequencies in the order of 100 cps upward (at tape speeds of 7½ ips) the only contributing factor is transformer action within the head. This wavelength phenomenon is encountered only during the playback process; the crosstalk contribution during the recording process is caused solely by transformer action. The less desirable crosstalk figures at long wavelengths, however, do not present a severe problem for audio use because the ear is so much more insensitive to frequencies in this range, and also because low frequencies (long wavelengths) are reported by Snow[2] to contribute little to stereophonic localization.

GENERAL CHARACTERISTICS

The mechanical dimensions are shown in Figure 2. The high tolerance on gap scatter, and therefore, tilt, is necessary to insure equal output from both channels at short wavelengths. In order to collect as much flux as possible, the cores overlap the edge of the tape, permitting a loose tolerance on core thickness. The tolerance for core-to-core spacing ($\pm$ 0.003 inch) allows approximately one-half db change in level because of tracking error.

The characteristics of the production heads must be reproducible relative to the nominal design curve (Figure 3) to $\pm$ 2 db from head to head, and be within 2 db channel to channel (within a given head). The output voltage is 0.8 millivolt at 250 cps at a tape speed of 7½ ips for a typical audio playback head.

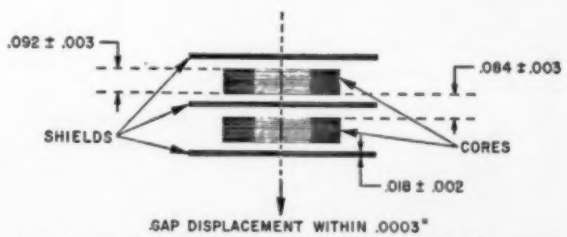

FIG. 2. Mechanical dimensions, in-line two-track stereophonic head.

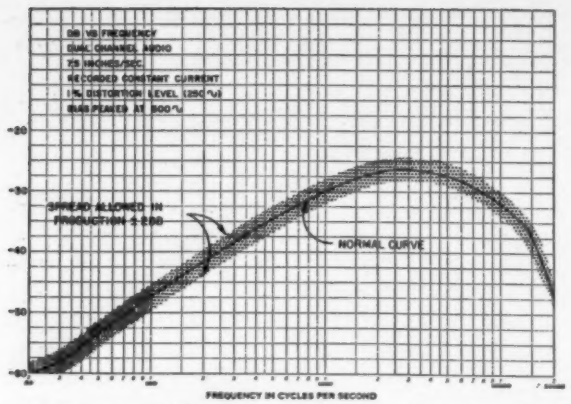

FIG. 3. Characteristics of production heads, showing allowed spread in tolerance.

The basic mechanical design evolved from experience gained in the design and production of very high accuracy multi-channel instrumentation and computer heads. The use of this design for audio applications is radically different from that used in the past. The small size of the head and the flexibility of the manufacturing process enable this head to be used in the lower cost machines as well as in the most costly professional equipment.

CROSSTALK

Long wavelength or geometrical crosstalk is of considerable interest, and may be explained as follows: As the wavelength increases, more of the flux surrounding a unit magnet on the tape will cycle through an adjacent core (Figure 4). The core spacing obviously stays constant; therefore, as the wavelength becomes shorter, the family of curves surrounding the magnet or unit magnet on the tape approach the actual recorded track more closely. Thus, as the wavelength is increased, more flux must cycle through the adjacent core, and will, therefore, induce a signal in the adjacent head. The best methods to minimize this problem are to surround the head with a shield such that some of this cycling flux will be shorted in the shield, and to keep the track-to-track spacing as large as possible.

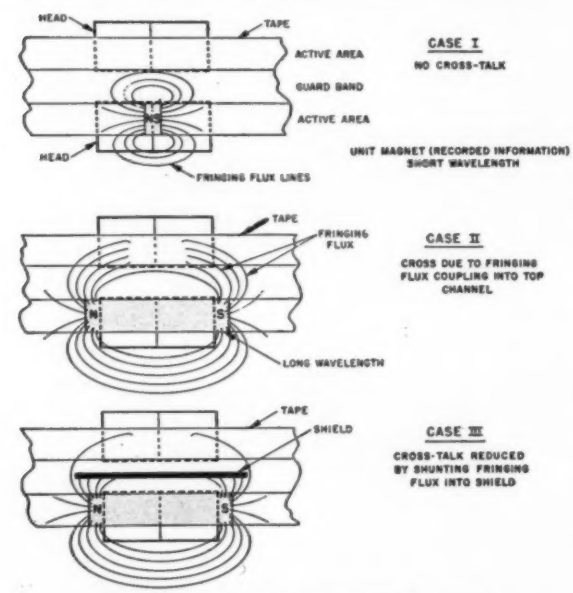

FIG. 4. Cross-talk as a function of flux on tape.

In the head under discussion, shielding is needed and used for two purposes. The first is to reduce transformer crosstalk to its minimum level; and the second to reduce the long wavelength phenomenon described above. It was found experimentally that shielding very much wider than that incorporated in the head further reduces the transformer crosstalk a negligible amount. The limiting factor is field leakage across the front of the head rather than through the shielding and into the cores. This field leakage (transformer crosstalk) is, to the first order, independent of the presence of tap. The wavelength phenomenon, however, is not, and is dependent only on the presence of tape.

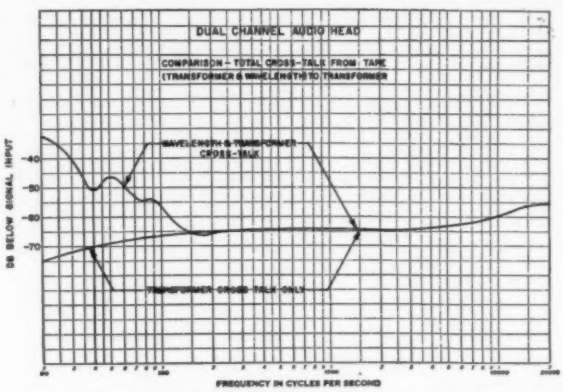

FIG. 5. Relative contributions of geometric (wavelength) effect and transformer action to cross-talk.

The increase in crosstalk in the high frequency portion of the spectrum is caused both by electrostatic coupling and resonant transformer action. As is well known, a resonant transformer requires a very low coupling coefficient to transmit energy between its primary and secondary.[4] Thus when the heads become resonant, the crosstalk increases somewhat. The contribution of each effect is shown in Figure 5.

[4] G. P. Harnwell, *Principles of Electricity and Electromagnetism*, (McGraw-Hill Co., New York), 2nd Ed., 1949, pp. 496-500.

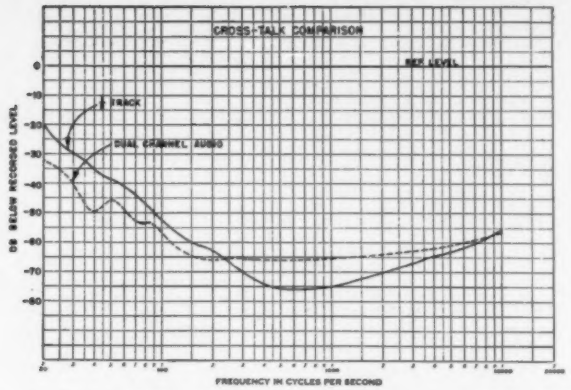

FIG. 6. Relative magnitudes of cross-talk present with typical half-track head compared with in-line stereo head.

A comparison of crosstalk is made in Figure 6 between a typical half track and stereophonic head. It should be noted that the crosstalk rejection is less at the low-frequency or long-wavelength portion of the spectrum with a half track head because the half track head has no shielding surrounding it and, as such, is more susceptible in the long wavelengths to crosstalk than the two-channel head. In the higher frequency regions, however, there is no core; therefore, no transformer action, and the crosstalk is slightly better.

The electrical curves of this nature are of considerable interest to demonstrate quantitatively the characteristic behaviour of the head, and for use in instrumentation machines. However, for audio purposes, a listening test is the most comprehensive. Therefore, a machine was set up with one high-level recorded track and a blank track. The blank channel was adjusted to high equivalent room level. The crosstalk was inaudible, and despite an increase in the equivalent room level of 30 db, little or no crosstalk was detectable even by the most discerning listener.

CONCLUSIONS

In summarizing we have characteristics as follows: Crosstalk in mid-audio frequency range better than 60 db. Gap scatter within 0.0003". Track spacing controlled to $\pm$ 0.003". Output of 0.8 mv at 250 cps at a tape speed of 7½ ips. The basic head design may be used for record and playback of stereo and half-track reproduction without inter-channel crosstalk interference. Small in size and reasonably inexpensive to produce, the head-to-head reproducibility is within $\pm$ 2 db, and the channel-to-channel reproducibility is within 2 db.

The authors wish to acknowledge with extreme gratitude the help of Ralph Conly, Robert Michaud, and William Pottberg, who were all intimately involved with the complete design phase of the head. Their ideas, suggestions, and active effort in the project assured successful conclusion.

Practical Aspects of Hot Stylus*

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Some practical solutions to problems which arise in the use of the hot stylus technique in disk recording are presented. The author considers (1) the matching of stylus to cutter head, (2) the influence of burnishing facet size upon frequency response, distortion, and head wear, and (3) the design of feather edge styli. Procedures for setting the optimum working temperature, the elimination of resonance effects, and adjustment of cutting depth are given.

THE HOT STYLUS

THE HOT STYLUS system to be discussed here is of the resistance type, and consists of #37 copper wire coiled around the gem of the stylus, and operated from a 2- to 4-volt dc supply. Approximately 6 in. of copper magnet wire were coiled on the body of the gem.

Common cutting styli were used in the initial experiments, with part of the resistance coiled on the shank of the stylus. The results obtained showed reasonable improvements in noise reduction, but too much heat was conducted to the cutter head by the aluminum shank. Exposure or increase in size of the gem solved this problem nicely, so that the resistance was coiled entirely on the jewel point.

The collaboration of a local stylus manufacturer made possible the development of (1) new types of stylus, with bigger jewel tips, (2) burnishing facets from zero to any size required, (3) special cements to strengthen the union of the jewel with the metal, and (4) the necessary degree of uniformity required between two specimens selected at random.

Unfortunately, the lack of uniformity was so great with styli obtained from reputable foreign manufacturers, that it forced the local stylus manufacturer to build a burnishing facet polishing machine which operated at the fantastic velocity of more than 250,000 rpm. This proved to be the only way to provide the very high degree of uniformity required between shipments.

Types of Stylus for Heated Cutting

With cutter heads of the plastic damping variety, such as Presto 1-D, RCA, etc., where the damping action of the blank material has an appreciable influence on frequency response, experiments performed with different types of stylus revealed the following sequence of results for a given type of master blank, which, incidentally, was Audio Master:

Capps' Anti-noise, peaked response at 6 kc with no substantial response above 7.5 kc.

Common master stylus provided a more uniform response with top limit in the 8-9 kc region.

Special types with smaller burnishing facets improved uniformly the top limit, up to the top limit of the cutter head, which in this case was a 1-D, about 11.5 kc to 12.5 kc was attained both for 78 and microgroove.

Feather edge type (zero burnishing facet) provided some measurable response at 15 kc, but the response over the spectrum, 2 to 10 kc, was full of imperfections, with peaks having the magnitude of 8 and 10 db, obviously caused by leakage of the damping action of the blank material.

This sequence of stylus types drove us to the following conclusion:

"With cutter heads employing plastic damping materials, the best compromise is to utilize a stylus with an extremely small burnishing facet, but this facet must always be greater than zero."

With cutter heads such as WE, Grampian, Orthofon, and other feedback types, where the damping action of acetate is not of primary importance, the stylus problem can be faced in a more precise manner. The experiments described below, aiming to find better stylus types, were made with a Grampian B1-AGU cutter head with the proper amount of feedback connected.

* Paper presented at the Eighth Annual Convention of the Audio Engineering Society, New York, September 26, 1956.

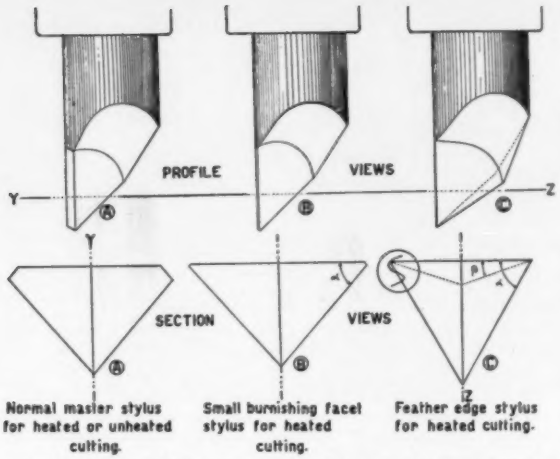

FIG. 1. Cutting styli shapes employed in the hot stylus technique. α is the angle included by the cutting facet and one auxiliary facet. The reduction of α to a smaller angle β results in a theoretically perfect feather edge stylus.

INFLUENCE OF BURNISHING FACET SIZE

Synthetic ruby was chosen for tip material, mainly because its hardness is greater than that of natural or synthetic sapphire.

In a stylus designed for cold cutting, the presence of a large burnishing facet is indispensable, but when the hot stylus procedure is utilized, the size of the burnishing facet can be reduced to zero, or almost zero, without materially affecting the noise level.

Normal styli have burnishing facets of 0.0003" for 78 rpm normal groove. This approximate measure decreases to 0.00014" for microgroove types. The profile of such styli can be seen in Fig. 1A.

A custom-built microgroove type was sent to us by some business friends from the United States. Measurements of the burnishing facets of these samples gave an average of 0.0001". Test cuts revealed that even this small dimension was too large for 33⅓ rpm microgroove recording, although at 78 rpm microgroove this small facet type proved to be 100% satisfactory, within the range of audibility.

Incidentally, 78 rpm microgroove recording is a very fine way to check the top frequency of the cutter head, provided a reasonable stylus is utilized.

The figure, 0.1 mil, being still unsatisfactory, new types of stylus were made with burnishing facets as small as one-third that figure, in other words, down to 0.00003".

With facets slightly smaller than 0.1 mil, say 0.08 or 0.07 mil, the upper frequency limit was extended, the increase being closely inversely proportional to the size of the facet; but, when the size of the facet reached a figure of 0.05 mil, curiously, this relationship between facet size and frequency ceased.

Close analysis revealed a very logical reason for this strange condition. Some element of the stylus, other than the burnishing facet, was now absorbing the vibrations of the highest frequencies. This proved to be the angle formed by one auxiliary facet and the cutting facet, as shown in Fig. 1B.

For the moment, let us call this angle α.

Some other effects had been observed before, that helped this analysis. One is the well known loss of the higher frequencies as the groove gets closer to the center of the record; the other is the limitation imposed on a 15-kc frequency at a medium-to-small diameter: that no matter how the amount of signal is increased, the recorded amplitude always remains approximately the same, and highly distorted.

New types of stylus were made with angle α somewhat reduced. This resulted in very noticeable improvements in frequency response, radius loss and the 15-kc acceptancy.

The angle α cannot be reduced below a certain minimum because for each degree that this angle is reduced, great amounts of material are removed from the tip of the stylus, thus increasing tremendously the fragility of the stylus tip, which now will break at the slightest effort, and render the stylus unsuitable for performing its functions.

A further small reduction of the burnishing facet is permissible after the readjustment of angle α, say, to 0.000035" $\pm$ 0.000005", our present figures.

THE FEATHER EDGE STYLUS

Parallel to the improvements made on the regular type of stylus, many experiments were made with another type of stylus, called "Feather Edge."

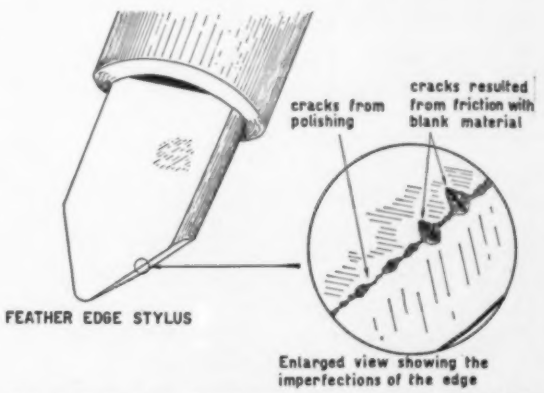
cracks from polishing
cracks resulted from friction with blank material
FEATHER EDGE STYLUS
Enlarged view showing the imperfections of the edge

FIG. 2. Schematic enlarged section of a feather edge, showing irregularities.

This type of stylus should have theoretically a very sharp edge, but practice has shown that under high magnification, this sharp edge is not as regular as it should be. A similar situation can be observed on a razor edge at relatively low magnification. The irregularities of the edge produce noise by scratching the walls of the groove. They are due to imperfections in polishing, to scratches made by the diamond dust employed, and to cracks made by the lacquer material itself. Figure 2 illustrates these irregularities.

In order to minimize this deficiency, some modifications were made in the fundamental design of the stylus, such as an increase in the angle α (see Fig. 1C, profile view). Special polishing was also introduced. Unfortunately, increasing angle α brings back the problem discussed with burnishing facet types, that is, absorption of higher frequencies by angle α.

The section view in Fig. 1C illustrates graphically what actually happens when the sound has a wavelength shorter than the physical size of the stylus. To produce a perfect Feather Edge stylus, the angle α should be reduced to a fraction, β, of that amount, which would thus allow such a stylus to cut frequencies of 20 kc at a groove radius of 4 inches without loss.

But even if it were feasible to manufacture such a stylus, with an angle of magnitude β, this stylus would break into pieces if lowered into any other recording material than soft butter on a warm day.

DISTORTION CHARACTERISTICS FOR SPECIAL STYLUS TYPES

Distortion is inversely proportional to the frequency range reached, or, in other words, the higher the frequency engraved by the stylus, the lower the distortion.

ADJUSTMENT OF OPTIMUM OPERATING CONDITIONS FOR THE LOWEST NOISE LEVEL

This adjustment was made by the use of a 2-ohm, 50-watt rheostat, connected in series with the copper wire resistance, working with 4 volts dc supplied by a motor car battery (Fig. 3). A milliammeter connected in the circuit provided the necessary reference for the adjustment. A 0-100 ma full-scale type was used in our case. The instrument was shunted with nichrome wire until the maximum deflection with the full voltage applied corresponded to 100 ma. After that, some test cuts were made to determine exactly the best working temperature of the stylus.

Playback of these test cuts indicated that the best operating region is from 45 to 68 on this arbitrary scale for the 78-rpm, 0.003" groove, and from 42 to 56 for 33⅓, 78 rpm, and 45-rpm microgroove, and from 45 to 60 for

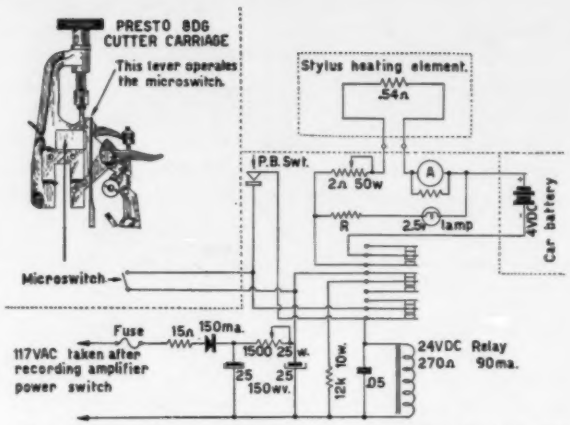

FIG. 3. Complete electrical diagram of the stylus heater, with the method used to mount a microswitch upon the carriage.

33⅓ rpm, 0.003" groove. Below these regions, noise increases gradually, and above, damage is done by the actual burning of groove walls, which also results in noise.

At even higher temperatures, breakage of the chip will occur, and the remaining part of it will accumulate around the stylus resistance, making a small fire that certainly will ruin the transcription, and the mood of the operator.

As the velocity of cutting diminishes with the diameter of the record, the temperature will vary a small amount from the outer to the inner groove, but the working region is sufficiently wide to accommodate this variation.

Room temperature also plays a small part, so the upper part of the working region should be avoided on warm days.

RESONANCE EFFECTS

Dilatation effects were also observed with this type of coiled resistance. They introduced noise in the recording, similar to that produced by a microphonic tube, although at barely perceptible levels. Total elimination of this effect was obtained by cementing the winding with inorganic cements. Zinc oxide cement, of the same type used by dentists proved effective for semi-permanent windings. A more permanent type of cement was obtained by using a combination of chemical substances in which the major ingredient was calcium sulphate.

DC *vs.* AC, THE GREAT CONTROVERSY

With direct current, there is a magnetic pull of the cantilever toward one of the permanent magnet poles, which although barely visible under a microscope, is enough to drive the cantilever out of its magnetic center, thus causing some

nonlinear distortion similar to that produced by vacuum tubes when the bias is incorrectly adjusted.

Readjustment of the magnetic center with the operating voltage applied to the stylus provides compensation for this effect.

Obviously, with an alternating voltage, the magnetic center changes at the rate of the applied frequency, causing nonlinear distortion to both sides of the wave, or, in other words, intermodulation.

HUMAN FACTORS IN OPERATION

Since the day that heated styli emerged from the laboratory to become an equipment facility in our company, some problems arose which were due exclusively to human faults in operation. These most frequently were related to the turning off of the hot stylus switch. Although the actual stylus temperature is not excessively high, some damage can result to the magnets and to the plastic damping material (if used in the cutter) if they are exposed to the heat for considerable periods of time.

This problem was nicely solved by incorporating a microswitch into the cutter head carriage, so that a 24-volt dc relay is actuated each time the cutter head is lowered. Figure 3 shows how this is done. Double protection is obtained by connecting the ac power supply of the relay so that the power switch of the recording amplifier turns it on.

CONCLUDING REMARKS

As a heated stylus somewhat softens the lacquer material, it is advisable to adjust the depth of the cut after the stylus is turned on.

Control of the suction pressure utilized for chip removal is highly desirable.

The finished appearance of records made by following the above techniques is shiny and rainbow-like.

When styli of special type are employed, the appearance of dull stripes on the shiny surface need not cause alarm.

The hot stylus technique in its present development has enabled the engineer to further experiment with those design factors whose optimum values in the past were controlled by the signal-to-noise level barrier. They were designed to, at best, decrease the noise level, but at the expense of all the other factors so necessary for a faithful recording.

In my personal opinion, the hot stylus ranks with negative feedback in amplifiers as a great contribution to the advancement of the audio art.

Acknowledgments

The author wishes to thank here Mr. Sergio Lara Campos and Mr. J. Gomes, from RGE and from Realtone, for the many good suggestions offered, which made this paper possible. The author is also deeply grateful to Mr. Julius Postal for the presentation of this paper.

Tape Recorder Flutter: Causes and Effects*

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United States Navy Electronics Laboratory

The widespread use of tape recorders for experimental purposes makes it necessary to establish the motion characteristics of tape transport mechanisms. At the U. S. Navy Electronics Laboratory investigations have been made of a wide variety of magnetic tape recorders. Factors affecting their flutter performance have been checked to insure the best possible flutter performance in Laboratory experimental use. This paper reviews results obtained from measurements, and compares flutter in several types of tape transport mechanisms.

EVERYONE in the recording industry has at one time or another been concerned with flutter or wow; it occurs in all recording equipment whether it be disk, film or tape.

Originally flutter was considered to be a simple variation in speed at a low rate. This could be expressed as a percentage rms value of the quotient of the change in frequency divided by the base frequency. Various base frequencies have been used, but the most common at the present time is 3 kc. This allows flutter rates up to 300 cps to be observed. As the use of recording has increased, especially for data use, this 3 kc base frequency was found to be too low. Instruments using a 40 kc base frequency have been built and used very successfully. Such equipment has been described by John T. Mullin of Mincom Division, Minnesota Mining and Manufacturing Co., in a paper entitled "Measurements of Flutter and Wow in Magnetic Tape Instrumentation Recorders."[1]

The equipment used by the authors of the present paper uses a 14.5 kc base frequency and therefore can be used on audio type recorders as well as on instrumentation recorders. High rate or scrape flutter is rarely a simple motion, rather it is found to be made up of short peaks of a random distribution. For this reason, peak-to-peak values were found to be a more realistic presentation. A cathode ray oscilloscope is an ideal instrument for this purpose. If a permanent record is desired an oscilloscope camera such as the Fairchild may be used.

The measuring equipment used at the Naval Electronics Laboratory includes a commercial flutter bridge which is manufactured by the D & R Manufacturing Company of Santa Barbara. Fig. 1 shows a block diagram of the test equipment. The equipment incorporates an oscilloscope which has a flat response from dc to over 5 mc. The equipment may be easily calibrated by feeding in a frequency of 14.5 kc from an oscillator, then shifting the frequency by calculated amounts, and adjusting the equipment for the correct output as indicated on the built-in oscilloscope. Once the oscilloscope is adjusted the output of a special 14.5 kc fm oscillator is fed in. The meter of the flutter bridge is adjusted to read .707 of the level indicated on the oscilloscope.

Figure 2 shows the effect of flutter on a video presentation. The left-hand side is a direct photograph of a PPI type of sonar presentation, the right-hand side is a photograph of the same information after it has been stored on tape and then played back into the sonar set.

Depicted in this figure are echoes from fishing boats and reverberation, along with a bearing cursor and the stern

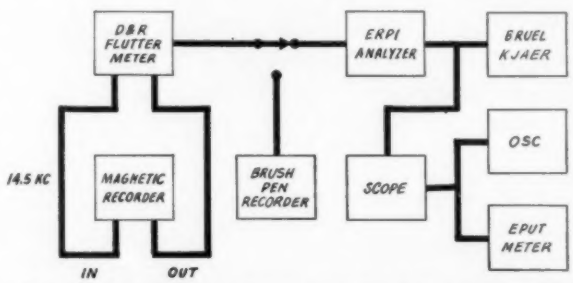

FIG. 1. Block diagram of test setup for flutter measurement. The flutter meter feeds a 14.5 kc am signal into the recorder under test and indicates the flutter rate of the output. Alternatively, the voltage at the discriminator of the flutter meter may be switched either to a Brush recorder or to an analyzer for observation.

* Paper presented at the Fifth Annual West Coast Convention of the Audio Engineering Society, Los Angeles, February 8, 1957. Revised manuscript received May 13, 1957.

[1] J. T. Mullin, *J. Audio Eng. Soc.*, 3, 151 (1955).

FIG. 2. Two PPI sonar presentations. Left: a direct photograph of the CRT. Right: the same information stored on tape and played back into the sonar set. Jitter noticeable in the stern pipper (vertical line) is produced by flutter in the tape recorder.

pipper. You will notice there is jitter in the stern pipper of the reproduced display. This is a manifestation of sweep instability caused by wow and flutter in the magnetic tape recorder.

Flutter is partly a function of mechanical design, and the watch word is precision; there is nothing that takes the place of precision in both the machine work and in the assembly. Figures 3, 4, and 5 show samples of flutter from various recorders. These figures are all of low rate flutter, that is, flutter in the range of .5 to 30 cps. Figure 3 is a light weight portable recorder, it relies chiefly on a heavy flywheel to achieve steady tape motion. However, at slow speed, the energy storage capacity is too low, and the flutter is quite high.

Figure 4 is the flutter on an older tape recorder that used a tight loop tape path. A tight loop machine should be

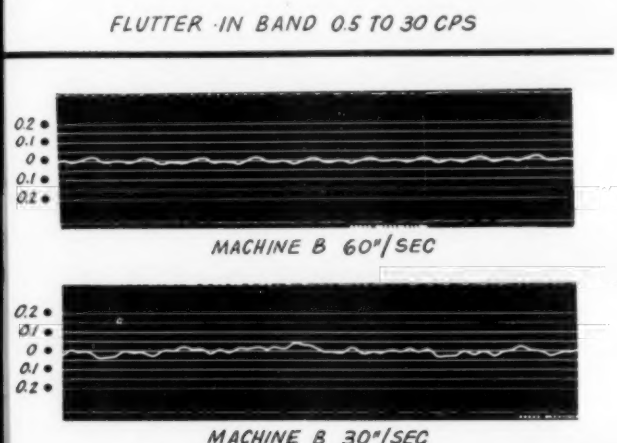

FIG. 3. Flutter in a light weight portable tape recorder. The increased flutter at 30 ips results from the inadequacy of a heavy flywheel to provide steady tape motion at the lower speed.

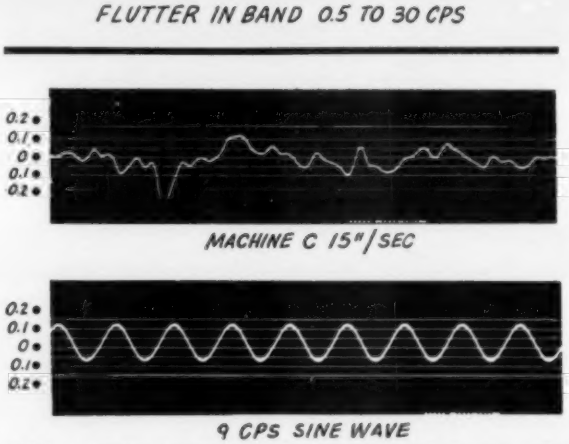

FIG. 4. Flutter observed on an older type tape recorder. The tight loop tape drive is a desirable feature, but flutter occurred due probably to age and poor mechanical condition.

quite good, as the pinch rollers on either side of the head should isolate the head and give the tape a very uniform motion. In a tight loop machine one must watch the unsupported length of tape and keep it to a minimum. We will show later that high frequency flutter is a function of the length of the unsupported tape. This machine turned out to have quite high flutter which was probably due to its age and poor mechanical condition.

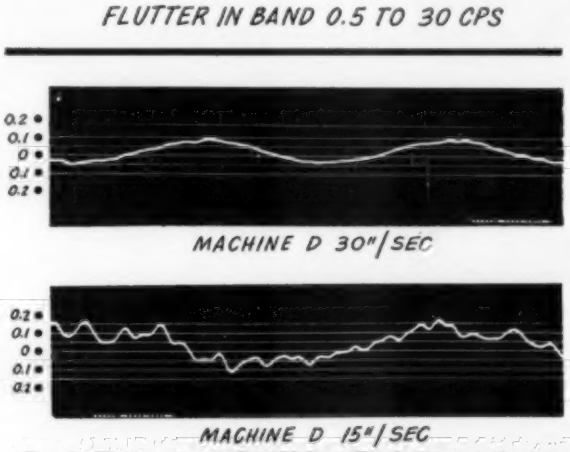

FIG. 5. Flutter on a modern high quality instrumentation-type tape recorder. This recorder shows the lowest flutter of the three types described.

Figure 5 is the flutter on a modern high quality instrumentation type tape recorder. This recorder incorporated not only a large flywheel and a form of tight loop tape travel but it also had the finest and most precise workmanship

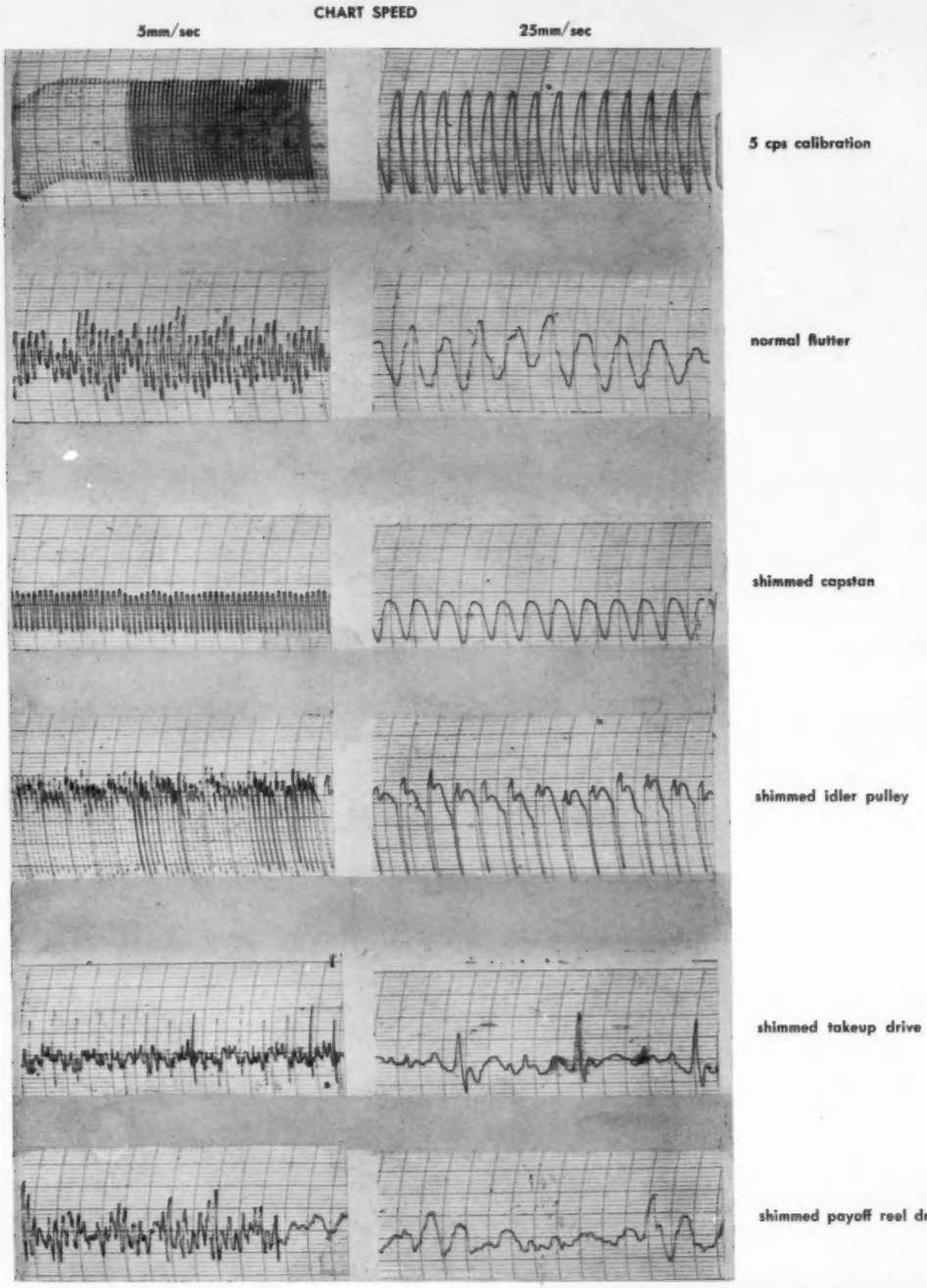

FIG. 6. Effects produced by artificially inducing flutter in a popular type tape recorder. The chart paper was run at 5mm/sec (left) and 25mm/sec (right). The first two traces show a 5 cps calibration run and the normal flutter. The remaining four figures result from applying shims at various flutter points in the transport mechanism, as explained in the text.

available. You will observe that the flutter is very low, the lowest of the three figures. This is also an expensive recorder.

Once we realize that flutter is a problem, the next step is to try to determine what is causing it, and of course, once that is determined, to eliminate or at least minimize it.

A procedure that has helped at NEL is shown in Fig. 6. Our procedure is to study the particular recorder we are interested in for possible flutter causes. Using a pen recorder, flutter tracings of the output of the flutter bridge discriminator are made. The next step is to introduce artificial flutter by shimming the various flutter points one at a time. By running traces for each condition and comparing them it is often quite possible to form a very good idea of what is causing the flutter.

The traces were made on a very popular and common type of two-motor, quality tape recorder. The chart speed was 5 mm/sec and 25 mm/sec as indicated on the traces. At the top of the figure we show a 5 cps trace for calibration of chart speed. Then there is some normal flutter, and below that there are samples of artificial flutter. From our traces it would seem as though there were a strong component around 3 cps and another one around 1.2 cps. Again, from the chart, the capstan rate is greater than this, so the capstan is eliminated as a flutter source. The pay-off reel does not make much difference so this is also eliminated. The idler pulley (in this particular machine) seems to have about the same rate as that of the flutter, while the take-up reel has a low rate around ½ cps which is similar to our observed flutter. From these observations it would seem to be worthwhile to look into the idler pulley for runout and rough bearings. The ½ cps flutter possibly is due to eccentricity of the take-up reel drive drum. The rates of the take-up and pay-off drums vary of course with the amount of tape on them, so all observations should be taken at about the same place on the reel.

Figure 7 is a photograph of flutter as it shows up on a Panoramic Sonic Analyzer, which had a low frequency cutoff at 100 cycles. The large pip indicates high frequency flutter around 2100 cps. In a paper entitled "Frequency-Modulation Noise in Magnetic Recording,"[2] von Behren and Youngquist have shown that the scrape frequency of tape is an inverse function of the distance between the capstan and the idler pulley. This particular machine measured 10 5/16 inches between capstan and idler. An interesting fact about scrape flutter, often referred to as "violin string effect," is that unlike a string it cannot be tuned by changing the tension. Experiments by Messrs. von Behren and Youngquist show that changing the tension affects the amplitude of the flutter but leaves the frequency unchanged. They also show that the heads preferably should be at one end of the span rather than in the middle.

The heart of a tape recorder is the capstan and the pressure roller. Since the former meters the tape it should be as true as it is possible to manufacture it. The instantaneous tape velocity is a function of the capstan runout or eccentricity, and an inverse function of the diameter. Hence, these dimensions are very critical during the manufacture of the recorder. Great care should be taken in the use of the recorder to protect the capstan from injury. For example, in a quarter-inch diameter capstan the eccentricity must be held to the order of 0.00010 inch if flutter is to be below 0.1%.

The two most common methods of tape hold-back are: (a) the constant torque motor and (b) the friction clutch. Other systems like the gravity clutch, magnetic clutches, and other servo-control systems have been built and used in the industry but have not been too popular for various reasons. We have found here at NEL that the constant torque clutch, given good maintenance, will serve very well, but that a constant torque motor requires almost no maintenance. Where weight, space and power limitations permit, the torque motor method of hold-back is to be preferred.

The energy stored in a flywheel is a function of weight and speed; therefore it is necessary either to have a large flywheel or to run it at high speed. In machines with a flywheel on the capstan shaft the speed is dependent on the size of the capstan; this gives us two conditions which are not compatible: either a small diameter capstan for good flywheel effect or a large diameter capstan for less flutter due to eccentricity.

Some tape recorders incorporate spring-loaded tension arms. These arms in conjunction with the flywheel act as a low pass filter. By proper choice of mass and compliance the pass frequency can be made extremely low, on the order of 1 cps. When a recorder is designed for a specific record-

SCRAPE FLUTTER IN TYPICAL AUDIO RECORDER

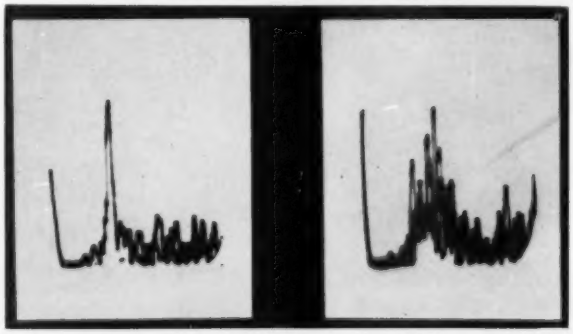

FIG. 7. Flutter as observed in a panoramic display. The peak, due to scrape flutter, is clearly evident at 2.1 kc.

[2] R. A. von Behren and R. J. Youngquist, *J. Audio Eng. Soc.*, 3, 26 (1955).

ing job where the recorded frequencies are in bands such mechanical filters can be very effective.

Another very good attack on flutter in specialized recorders is electronic compensation. The general method is to mix an unmodulated carrier with the modulated carrier and to record the result. On playback the unmodulated carrier which will have the same amount of flutter as the modulated carrier, is separated out, shifted in phase, and fed back into the information channel so that the flutter cancels out. Electronic compensation will reduce the effect of mechanical flutter to 20% of its original value.

In conclusion, in tape recording as in a great many other things, you get what you pay for. So far, there does not seem to be any cheap and easy way to lower flutter.

THE AUTHORS

Earle F. Travis was born July 16, 1913 in Boston, Mass. A graduate of Cleveland Institute of Electronics, he spent ten years as chief engineer of KVEC. Since 1951 he has been a member of the Recording Section of the U. S. Navy Electronics Laboratory, San Diego, California.

Lawrence L. LaZelle dates his early interest in electronics and audio to the early 20's when he built small radio receivers for his friends and to the 30's when he operated his own sales and service business. During World War II he spent a year in the Radio Department of Convair and later worked for the University of California Division of War Research in San Diego, which later became the present U. S. Navy Electronics Laboratory. For the past eleven years he has been a member of the Recording Section of the Laboratory.

He is presently Chairman of the Professional Group on Audio of the IRE, San Diego Section, Vice-Chairman of the San Diego Section of AIEE. He is a member of the SMPTE.

Solution to Some Problems in Making Master Tapes*

R. J. TINKHAM

Ampex Corporation, Redwood City, California

TOO OFTEN, user complaints about the performance of tape recorders are based on a lack of understanding of the basic principles involved in the magnetic recording process, and of how to apply these principles in making top quality tapes. Too many users think of recording as merely a matter of pushing buttons, and fail to realize that bad results may be the fault of the machine adjustment, the tape, or of the operator.

As time goes on our customers become more critical of our techniques, and competitive pressure sees to it that the product improves. One manufacturer will improve the recording process and capture the market for a while. Then his competitors catch up or beat him to an even better product, like the LP.

Tape recording for making masters, and microgroove cutting went hand in hand to create the biggest boom the recording industry has ever had. The use of tape for the original recording gave to the recordist the immediate advantage of providing an erasable, reusable, editable medium. To the performer these features meant a relaxed performance. No longer was the artist under pressure to make a complete performance without flaw; the tape editor's scissors took care of that. No longer did the operator, during the recording, need to worry about dull cutting styli, or wax playbacks, or hard spots in the instantaneous lacquer disc. No, now he had a lot of other worries, of which he was only dimly aware. They related to how to achieve quality on tape.

MASTER TAPE QUALITY

What constitutes good record quality in this "mid-morning era" of magnetic tape recording?

A good master tape is characterized by the following attributes:

1. Low distortion
2. High signal-to-noise ratio
3. Wide and uniform frequency response
4. Freedom from mechanical (tape) defects

Any recording system, be it tape, wax, or film, will tend to distort if overloaded. Therefore, to minimize this problem, one should reduce the recording level. All recording systems inherently have noise. Therefore, to minimize this problem, one should increase the recording level.

Frequency response suffers at low tape speeds, therefore speed up the tape, or pre-emphasize at the higher frequencies, to compensate for this. But good magnetic recording heads are expensive; therefore, some favor reducing the tape speed so they'll last longer (this isn't really true).

We are thus impaled on the several horns of a dilemma, and find it necessary to make a series of compromises in building a tape recording system. One must consider tape speed, frequency response, distortion, flutter and wow, the chemistry and physics of the tape itself, and the relationship of each of these factors to each of the others. For example, the successful compromise in tape recording has now led us to a quality of reproduction meeting or exceeding these overall specifications:

1. Distortion: 1% harmonic at 400 cps, overall.
2. Signal-to-noise ratio: 60 db.
3. Frequency response: 40 to 15,000 cps $\pm$ 2 db.
4. Flutter and wow: 0.1%.

That is, if everything is working correctly:

1. The machine must be in good working order,
2. The tape being used must be satisfactory,

and most important:

3. The machine must be adjusted to match the tape being used.

I wish to call your attention particularly to point number 3: The machine must be adjusted to match the tape being used. There is an implication here which all no doubt will have detected: tapes are not all the same. Even tapes from the same manufacturer will differ from batch to batch. But more of this a little later.

CAUSES OF POOR QUALITY

The failure to achieve a satisfactory tape master can be due to any one of a number of causes, or to a combination of these causes, such as:

* Delivered at the Eighth Annual Convention of the Audio Engineering Society, New York, September 26, 1956.

1. Poor or damaged microphone.
2. Harmonic distortion, frequency distortion, or noise, introduced ahead of recorder.
3. Mechanical maladjustments or damage to recorder.
4. Improperly aligned recorder, i.e.:
   (a) incorrect head azimuth alignment.
   (b) improper record equalization and/or playback equalization.
   (c) incorrect bias adjustment.
5. Magnetized heads.
6. Improper recording level (too high, or too low).
7. Unsatisfactory tape.
   (a) dropouts
   (b) inherently poor frequency response (too "hot" or too "cold")
   (c) mechanical faults (coating, flaking off, high friction, curl, or improper slitting)

The scope of the remainder of this discussion will be confined only to the intimate relationship between the recorder and the tape itself.

It must be assumed that any mechanical or electrical maladjustments have been detected and corrected. Too often we find that an improper diagnosis has been made, and incorrect measures have been taken to correct malfunctions; it is well to double-check anything that is suspected. It is further assumed that the operator is familiar with the basic alignment procedures described in the instruction book accompanying professional recorders. Too much emphasis cannot be placed on following the correct procedures; most complaints about poor operation of equipment must be attributed to incorrect alignment procedure on the part of the operator. Professional tape recording machines are purposely made adjustable so that optimum quality recordings may be secured, but an adjustment incorrectly made will lead to just the opposite result. A good tape machine, like a racing car, is capable of being tuned to a fine line of performance, or it can be badly de-tuned.

PROPER ADJUSTMENT

Perhaps a word here about proper adjustment is in order. First of all, we are seeking a correct reproduction of the recording; this means *playback* characteristics should be standardized. This also means that any variation in machines, tapes, or methods of recording should be compensated for, in some manner, before playback.

Rather excellent uniformity has been achieved by at least one manufacturer of professional recorders in this respect. This company[1] produces a series of so-called "alignment tapes" at various standard tape speeds. These tapes enable one to adjust the playback section of a recorder (if it is capable of being adjusted) to a known characteristic. This includes head azimuth alignment, gain, and uniform frequency response.

[1] Ampex Corporation

After the playback section has been standardized, the next consideration, of course, is to modify the *recording* section to yield the proper type of pattern *on the tape* so that it will play back properly over the previously standardized playback section. This point seems rather obvious, but we are constantly surprised at the number of people who either overlook the obvious, or are unaware of it.

Most factories producing tape recorders have some sort of checkout procedure involving the playing of a piece of tape. The professional machines are adjusted usually to the "average" tape available on the market at the time of manufacture.

TAPE VARIATION

It was mentioned that the checkout tape is an "average" tape. It must be recognized that the various manufacturers of tape may have different oxides, use different binders, or use different manufacturing methods to build their tapes. Obviously, then, one may expect that there would be differences in the several characteristics of tape one obtains from the different manufacturers. Indeed there are differences, but fortunately some professional recorder manufacturers make their machines sufficiently adjustable, so that these differences may be compensated for. It must be further recognized that the tapes of any given manufacturer may vary somewhat from batch to batch, with reasonable and normal manufacturing tolerances, and from year to year there is a slight shift. Then, of course, one manufacturer will get the "jump" on his competitors by bringing out a new tape, which may be markedly different in its inherent characteristics. This poses additional problems for the professional manufacturer and user alike, if they are to take full advantage of these new qualities.

All tapes will be found to vary with respect to one or more of the following characteristics:

A. Electrical
   1. Bias point.
   2. High-frequency response.
   3. Distortion (throughout the pass band).
   4. Overload characteristic (throughout the pass band).
   5. Variations due to uniformity (or lack of it)
      a. variations in frequency response
      b. variations in bias requirement
   6. Signal-to-noise ratio.
   7. Sensitivity.
   8. Remanence.

B. Physical
   1. Abrasiveness.
   2. Coefficient of friction.
   3. Adhesion of oxide to base.
   4. Drop-outs (electrical or mechanical).

Fortunately the variations among tapes for the many non-critical users are insignificant, and almost all tapes are found to be sufficiently uniform for enjoyable listening.

Not so for the professional, however. For this critical

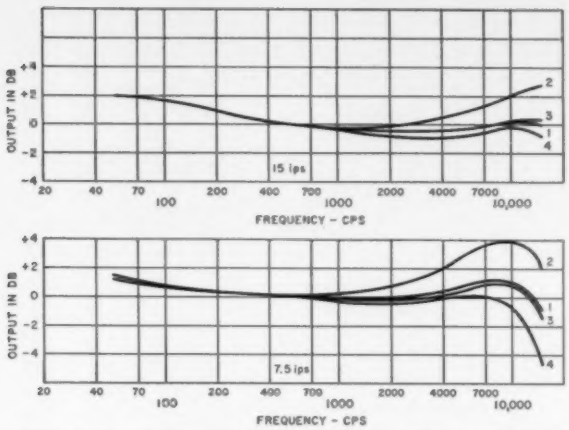

FIG. 1. Frequency response of four tape samples at 15 ips and 7½ ips. Bias and input level set at optimum.

group, who often must make second, third, and perhaps even further generation copies (should one say "degenerations"?), it becomes a virtual necessity to optimize the relationship between the tape and the machine to achieve the desired results. If we accept this condition as a reality, then we can optimize this recorder-tape relationship by following a series of steps for any given piece of tape.

TAPE DIFFERENCES

Before going further into the matter of adjusting the recorder to compensate for tape differences, let us examine in detail how tapes may vary. We will look at four carefully selected random samples; "carefully selected" to bring out the points to be discussed, and "random" in that they come either from different reels, or from different parts of the country, or from different manufacturers, or at different times.

Figure 1 shows how these four samples of tape perform under the same conditions. The bias adjustment of the recorder and the input level were set at optimum and left that way. The frequency response variations shown in the curves are inherent in the tapes themselves. Some are "hot"; some are "cold". There is more variation at 7½ ips than at 15 ips, as might be expected.

Figure 2 has to do with overload distortion. The curves show how these same four tapes overload at 10 kc. The bias setting has not been changed. This shows the output-input relation, when the input level is varied. Overload is affected of course, by the normal high frequency pre-emphasis in the record amplifier. This is the same, however, for all four of the tapes. Note the difference between 7½ ips and 15 ips. The playback equalization is the same for both speeds.

A word of caution here. One notes that the "operating level" line is considerably above the overload values for tapes at 7½ ips. Remember (1) that these curves are for 10 kc; (2) that pre-emphasis in the recording amplifier amounts to 16 db at 7½ ips, and 6 db at 15 ips; and (3) that this pre-emphasis is entirely legitimate when one considers the conventional energy distribution curves for music.

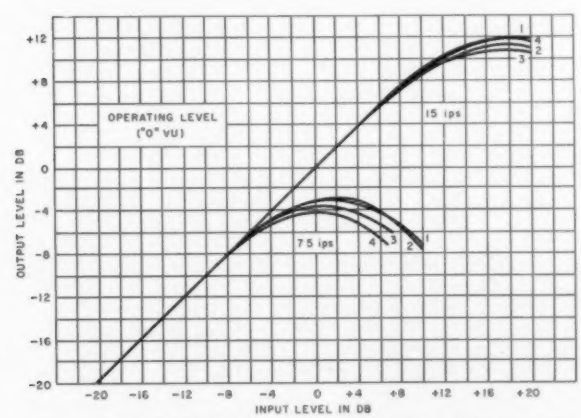

FIG. 2. Overload characteristics of four tape samples at 10 kc. Bias and speeds as in Fig. 1.

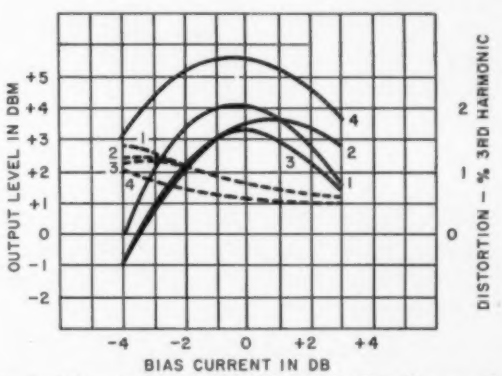

FIG. 3. 500 cps output and third harmonic distortion as a function of bias at 7½ ips. The solid curves represent the output level, while the dashed lines indicate % distortion.

Figure 3 shows the effects of changing the bias on these same four tapes. The speed of the tape is 7½ ips. The frequency used here is 500 cps. The input level is constant. The "hump-backed" curves show output level for changes in bias. At the same time one may observe the simultaneous effect which an increase in the bias current has on the reduction of the third harmonic distortion. These are the curves sloping downward to the right. Same four tapes; constant input; varying bias. Second harmonic dis-

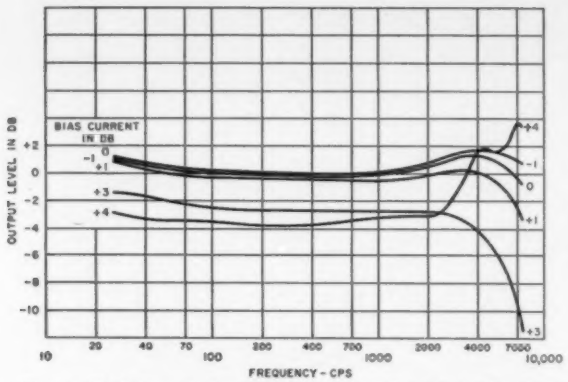

FIG. 4. Variations in frequency response and output with changing bias current. (Sample tape #1.)

tortion (in high-frequency biased magnetic recording systems) is negligible.

Figure 4 now looks at only one of the four tapes, and shows what happens to frequency response when the bias is varied. As the bias current is raised, the high frequency response deteriorates. The changing of bias is one way, and a legitimate way, to change the response characteristic. But, in using bias adjustment for equalization change, one must remember its effect on distortion.

Figure 5 again is for the one tape used in the test of Fig. 4. This shows at 500 cps what happens to distortion as the output level from the tape changes.

The effect of bias on the signal-to-noise ratio is shown in Fig. 6. At the top (same as Fig. 3) it shows the output levels and distortion for our original four tapes, and in addition now shows also what happens to the background noise (curves at the bottom) as the bias is changed. Since the ear is most aware of tape hiss rather than hum, we have used a 200-cycle high-pass filter in making these curves, as this is more representative of what we hear.

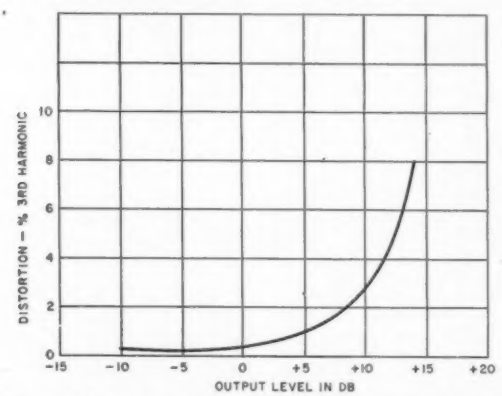

FIG. 5. Third harmonic distortion at 500 cps as a function of output. (Sample tape #1.)

Figure 7 shows the usable range of our four tapes. The bottom end of each bar is the practical background noise level inherent in the tape. The top end of each bar is the 1% harmonic distortion level (using 500 cycles). This shows that if one makes a recording on tape 4, for example, where his peaks hit "zero" on the meter, he may be sacrificing as much as 3 db in signal-to-noise ratio. This is a good reason for checking a given piece of tape for the 1% distortion level—and noise level. Tape X is a sample from behind the "Iron Curtain"; an interesting comparison.

From these typical data, shown in the figures, one can

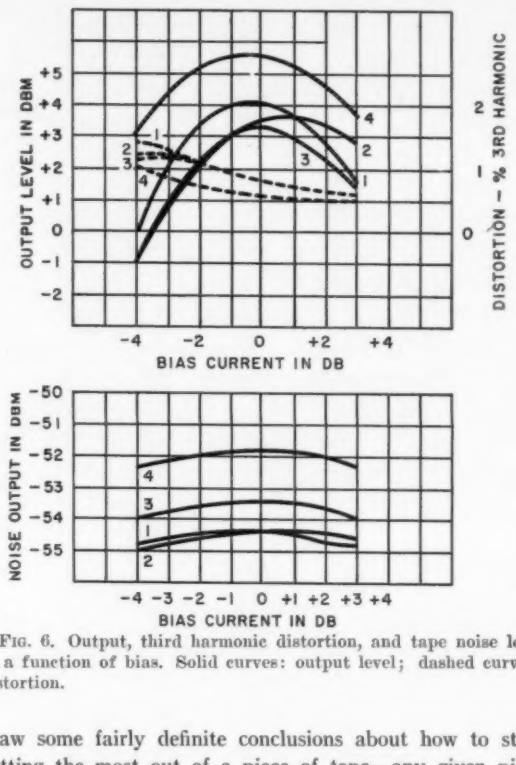

FIG. 6. Output, third harmonic distortion, and tape noise level as a function of bias. Solid curves: output level; dashed curves: distortion.

draw some fairly definite conclusions about how to start getting the most out of a piece of tape—any given piece of tape. Remember, we are still discussing master tapes.

It is obvious that 15 ips is better than 7½ ips when one considers overload distortion and uniformity of frequency response. The cost of the tape will be twice as great, but for a master this would seem to be of no consequence. Differences in head wear at the higher speed are also negligible from a cost standpoint, and incidentally, this is less than two to one. It is obvious also that optimum bias will give better results. But even here, one may use higher bias current for less distortion on a tape with especially good high frequency response, and gain overall.

Last, and probably most important, is signal-to-noise

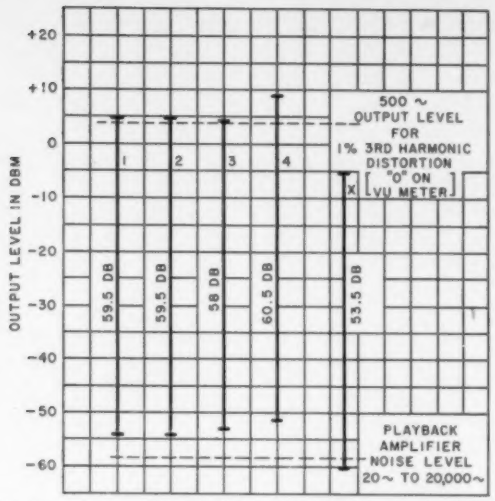

FIG. 7. 500 eps output level for 1% third harmonic distortion. The dashed line at the top represents "zero" on the VU meter. The upper extremity of each vertical bar indicates the 1% 3rd harmonic distortion point for that tape sample, while the lower extremity indicates the background noise inherent in the tape.

ratio. At 15 ips we have the best overload condition with respect to a higher input signal. We have had operators tell us that they record 3, 5, 7, even 10 db below the "zero" indicated recording level "to keep the distortion down". Some are needlessly penalizing themselves. Is this propensity for recording "x" db below zero justified? Without wishing to tread on anyone's feelings, I would suggest that some of this excess margin may be due to timidity.[2] Remembering that all magnetic recording is a compromise, let's just see how far we really can go by means of an example.

On a demonstration tape we made a series of recordings in different ways. It opened with a section of the original 15 ips tape (i.e., a "master") of an internationally famous orchestra which was recorded by the author with occasional peaks hitting + 3 db. The tape was played back at what we shall call optimum playback level. This was followed by a 1:1 copy of the same segment recorded, and reproduced, at the same level; then by another segment with the recording input gain raised 6 db. The output was reduced by 6 db so that the acoustic level remained the same. In the last segment the recording gain was reduced by 6 db, and the playback gain increased 6 db to compensate. This gave a difference in recording level of 12 db between the latter and the preceding segment.

The change in signal-to-noise ratio between these various copies and the original is marked, and to anyone making a similar comparison it will illustrate the fact that perhaps we should record at higher levels than we have been.

Thus far we've been dealing only with 15 ips copies. What happens when we cut the speed in half?

The signal-to-noise ratio at 7½ ips is (on an equal distortion basis) necessarily less than that at 15 ips, even though the same playback equalization is used. Recording pre-emphasis is much greater at the lower speed, which gives one a choice of slightly reduced recording level or of increased distortion. A 15 kc tone has a one mil wavelength at 15 ips, and only ½ mil at 7½ ips. This poses problems of head construction and azimuth alignment, and the bias setting becomes more critical. Because of the heavy pre-emphasis, the slower tape speed demands a tape which is more uniformly good at high frequencies.

SUMMARY

It is axiomatic that differences exist in the electrical (and physical) characteristics of tape.

To achieve optimum results one must adjust the recorder to match the tape to be used. A professional recorder may be so adjusted in the following manner and sequence:

1. Adjust the playback section for uniform frequency response and level, using a known standard alignment tape.
2. Adjust the bias, using the proposed recording tape.
3. Adjust the recording equalization to yield a flat playback from the previously adjusted playback system. Check this at least 10 db below normal recording level when using 15 ips and at least 20 db below normal recording level when using 7½ ips to avoid high end overload.
4. Check the recording level, and keep it high as practical in light of both signal-to-noise ratio and overload considerations.

The best results will be achieved by selecting tape which will give best frequency response with lowest distortion, and by adjusting the bias to achieve this balance. Good signal-to-noise level will be achieved by recording at a sufficiently high level; fortunately, the overload characteristics of tape are gradual rather than abrupt. One last observation: because of the fact that tapes differ in sensitivity, as evidenced in Fig. 7, it may be concluded that master tapes should be made at various levels—some loud, some not so loud; the playback gain control then becomes a useful component. Conversely, *perhaps* all commercially recorded (prerecorded) tapes should be made for reproducing at one level instead of at the best.

Acknowledgments

The author is indebted to Harold V. Clark, engineer in charge of the Ampex Standard Tape Lab for running the data on many, many hundreds of tapes from which our illustrative "random selection" was taken; and to John Leslie, Chief Engineer, Audio Division of Ampex, for his helpful suggestions on the arrangement of the data.

[2] This opinion of the author will be greeted in many quarters with uplifted eyebrows. (Ed.)

Evaluation of Tape Recorders*

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This paper describes both a philosophy and a number of techniques for evaluating magnetic tape recorders. For purposes of evaluation, a tape recorder may be considered as three units: the tape transport mechanism, the magnetic heads, and the electronic circuits. The tape transport must be tested for its ability to carry the tape past the heads at a uniform velocity, as well as for its auxiliary functions of fast-forward and rewind. The recording and playback heads must be evaluated for output, bandwidth, and uniformity of response. Finally, the electronic circuitry must be evaluated for low noise, low distortion, and proper equalization. An over-all test may then be made to complete the evaluation. Figures are included which illustrate the various techniques recommended for evaluating magnetic tape recorders.

INTRODUCTION

AT THE OUTSET it would be informative if a definition be given for the words "Evaluation" and "Tape Recorders" for the purposes of this paper. The generally accepted meaning of the word "evaluation" is, "to ascertain the value of", or "to appraise". We may expand this definition in the case of tape recorders as follows: evaluation is (1) the exhaustive testing for conformance to specifications, and for conformance to those standards which may be applicable; and (2) the critical comparison of performance and price against intended use. In other words, evaluation includes, but is not limited to, the careful testing of performance, and, when properly done, may well contribute to the improvement of existing specifications and standards as well as to provide guidance and motivation towards improving the design of the recorders themselves.

As to the definition of "tape recorders" there is here a considerable field from which to choose. Needless to say, the reference is to the *magnetic* tape recorder, but this term could apply equally well to the most costly instrumentation recorder as well as to the least expensive home machine. Many of the remarks might apply in general to the evaluation of all tape recorders (and in fact are based partially on experience with instrumentation types). The examples are drawn, however, from evaluations of those magnetic recorders which might be termed semi-professional, portable, tape recorders, and which are used for the serious recording of vocal and instrumental music.

* Paper presented at the Fifth Annual West Coast Convention of the Audio Engineering Society, Los Angeles, February 8, 1957. Revised manuscript received August 26, 1957.

† Reliability Engineer

EVALUATION PHILOSOPHY

For the purposes of evaluation, the tape recorder may be considered as three units: (1) the tape transport mechanism, (2) the magnetic heads, and (3) the electronic circuitry. The primary job of the tape transport is to carry the tape past the heads at a uniform velocity. The customary way of measuring this characteristic is in terms of flutter. Recent work by Comerci[1] has shown that the human ear is sensitive to rms values of flutter. Furthermore, for speech and music, the flutter perceptibility threshold is 0.3% rms at a flutter rate of 3 cps, increasing to 0.5% at 1 cps, and to about 1.0% at 20 cps. It is apparent then that an evaluation of the tape transport mechanism must include a measurement of flutter to assure its compliance with these requirements. Timing tests may also be performed to determine the long-time accuracy of tape velocity where the intended use requires it. High frequency flutter at rates of 2 kc or higher is probably not as serious for entertainment recording as it is for instrumentation recording and is therefore not considered. Of the various methods used for driving the capstan, the elastic belt drive of a capstan flywheel appears to be the best for portable recorders. It avoids the drawbacks of an idler drive and allows a single motor to perform the capstan drive, takeup, and rewind functions. With a single motor drive, the takeup function is usually provided by a slipping belt or a felt clutch. Of the two, the felt clutch usually gives less flutter when properly designed and maintained. Magnetic clutches have also been used, but no data are available on their performance.

[1] F. A. Comerci, "Perceptibility of Flutter in Speech and Music", *Trans. IRE-PGA*, AU-3, pp. 62-70 (May-June 1955).

The magnetic heads deserve careful evaluation also, due to their critical function as transducers of electrical current to magnetic patterns on the tape and vice versa. Extensive studies have appeared in the literature on the theoretical[2] and practical[3] aspects of head design. It has been well established that, of the three major configurations in general use today, the ring head has proved most satisfactory from the standpoint of uniform and wide range response. At this point it would be appropriate to introduce a figure of merit which the author has found useful in judging various types of magnetic heads. This concept might be termed the "bandwidth" of the magnetic head. It is generally recognized that the response of a magnetic recorder at short wavelengths is limited by the gap length of the reproduce head. It is equally true that, at long wavelengths, the response is limited by the over-all head length; undulations in the frequency response appear at wavelengths which approach the longitudinal head dimensions. It follows that the "bandwidth" of a magnetic reproducing head is a function of the head length divided by the gap length. Since successful reproduction is seldom achieved at wavelengths greater than twice the gap length, and since the long wavelengths begin to suffer beyond one-half the head dimension, we might define the bandwidth of the reproducing head as:

$$BW = L/4G,$$

where L = head length (that is, the effective length where the tape contacts the pole faces), and G = gap length (in the direction of tape motion, often erroneously called "gap width"). Using this criterion then, a representative ring head might have a bandwidth of 500 whereas an overlap type of head might have a bandwidth of only 15! (The overlap type of head has its laminations vertical and the gap is formed by the overlap of two or more of these laminations.)

Another important parameter of a reproducing head is its Q. Generally speaking, the higher the Q the better the signal-to-noise ratio, assuming equal output. This is a result of fact that the effective resistance, and hence, the Johnson noise is lower. Q's in the range of 7 to 10 at 1 kc are considered satisfactory.

The electronic circuitry plays a very important role in the overall performance of the recorder, particularly in the functions of amplification and equalization. Perhaps the most critical point in the circuitry is the playback amplifier. Various techniques have been devised to lower noise at this point: tube selection, use of special low-noise tubes (both triodes and pentodes), and use of special circuitry. It is unfortunate that the latter approach has not been more widely used. It has been shown, for example, that the cascode circuit can give equivalent noise levels at the grid as low as 0.35 microvolt over the audio band,[4] whereas the use of even special low noise tubes in standard configurations seldom results in noise levels below 2.0 microvolts under similar conditions. The importance of this can be realized by considering the fact that the head output at low frequencies may be of the order of 500 microvolts. A noise level of 2 microvolts would only permit a signal-to-noise ratio of about 48 db, and the amplifier might well become the limiting factor in system performance. Another critical point in the circuitry worth mentioning is in the bias-erase oscillator. The desirability of low second harmonic distortion in the bias-erase waveform has been pointed out a number of times. The push-pull Colpitts (or negative resistance) oscillator is capable of good performance in this respect. However, we still see single-ended oscillators of various types in use even though the savings in cost and power consumption appear to be negligible.

The subject of equalization is a very controversial one. The lack of standards at a tape speed of 7.5 inches per second (and slower) can well lead to the chaos that we had in the record industry before the adoption of the RIAA characteristic. It appears that the reproducing characteristic (at the high end) for 7.5 ips should lie somewhere between the present NARTB standard for 15 ips of 50 microseconds and the CCIR recommendation of 100 microseconds. A reasonable compromise might well be 75 microseconds (turnover of 2120 cps) which would alleviate tape overload by requiring less pre-emphasis of the high frequencies. It is believed that the slight loss in signal-to-noise ratio could be made up by using the circuit technique recommended above. The low end, on the other hand, might benefit with a bit more pre-emphasis as a help in rejecting discrete hum frequencies (which often prove more annoying than white noise). A turnover at 100 cps (RC = 1590 microseconds) in the reproduce characteristic might well be considered. The additional pre-emphasis of 3 db at 50 cps which would be required is not likely to cause overload except on high level organ recordings. It is worth mentioning that the motion picture industry routinely uses up to 7 db of pre-emphasis at 50 cps without apparent difficulties.

EVALUATION TECHNIQUES

Frequency Response

A very desirable method of measuring frequency response uses a level recorder. Besides saving considerable time over the point-by-point method, it will often show up ir-

[2] W. K. Westmijze, "Studies on Magnetic Recording", Phillips Research Reports, 8, pp. 148, 161, 245, and 343 (1953).

[3] O. Kornei, "Structure and Performance of Magnetic Transducer Heads", *J. Audio Eng. Soc.*, 1, 225 (1953).

[4] R. L. Price, "The Cascode as a Low Noise Audio Amplifier", *Trans. IRE-PGA*, **AU-2**, No. 2 (1954).

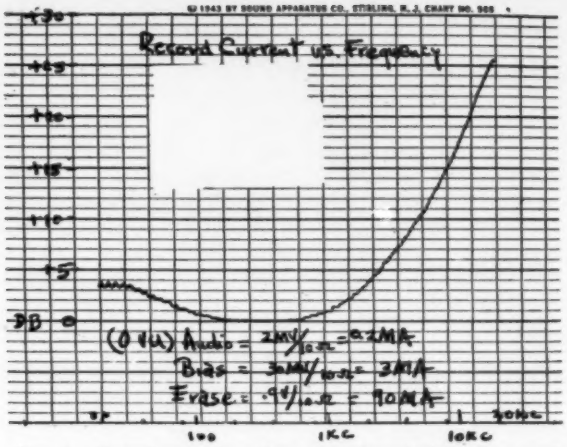

FIG. 1. *Record current vs frequency* characteristic of a semi-professional tape recorder. A constant amplitude output of a BFO was fed into the record amplifier and swept across the spectrum in synchronism with the chart paper. The vertical axis represents the output as developed across a 10 Ω resistor connected in series with the record head.

regularities that will not be evident in the latter method. Figure 1‡ shows the *record current* versus *frequency* of a typical semi-professional recorder (7.5 ips). This measurement was made by introducing a constant amplitude signal from a beat frequency oscillator into the line input of the recorder and taking the output across a 10-ohm resistor in series with the head (bias disabled). The output is recorded as a function of frequency as the oscillator is swept through the af spectrum in synchronism with the recorder. Commercial dial drives are now available for this purpose.

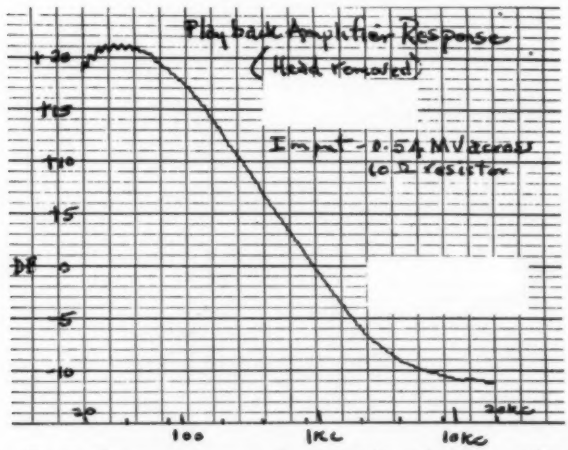

FIG. 2. Frequency response of corresponding playback amplifier (head removed). The signal was applied directly to a 10 Ω resistor across the input.

‡ Figs. 1 to 6 are official U. S. Navy photographs.

Fig. 2 illustrates the playback amplifier response of the same recorder plotted in a similar manner. Note that the signal is introduced directly into the playback amp (head removed). Fig. 3 shows the effect of head resonance. In this case, the signal is introduced across a small resistor in series with the head. A rise of about 3 db in the vicinity of 15 kc can be noted. Figure 4 is the overall response of the recorder taken at a record level of –5 VU. Note the "birdie" or beat tone at the high frequency end, indicating tape overload. This is clearly audible on playback. Figure 5 is the overall response taken at –15 VU. Note the disappearance of the beat tone. Certain small irregularities have appeared at the high frequency end. This effect is probably the result of small deviations of the pole faces of the reproduce head from exact parallelism.

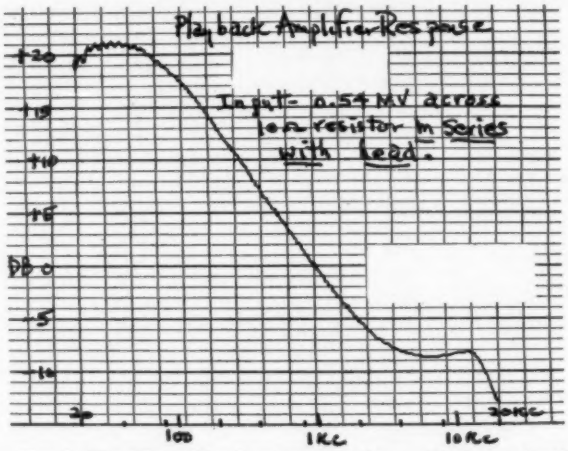

FIG. 3. The effect of head resonance is shown. The input signal was applied to the 10 Ω resistor in series with the playback head. A rise of about 3 db at 15 kc is prominent.

The last illustration, Figure 6, is the typical response of a machine using an overlap[5] type of head for recording and reproducing. The irregularities below 2 kc were shown by separate test to arise in the playback process. The irregularities above this frequency were put on the tape during the recording process. Irregularities of this magnitude can hardly be justified in a recorder of this price class. It is interesting to note that the manufacturer of this machine publishes a point-by-point response curve which is substantially flat. An alternate method of testing has been proposed[6] which uses a test tape. This method is useful for those who do not have access to a level recorder. However, it would be desirable if the manufacturer of the test tape

[5] A. H. Mankin, "Interference Effects in Magnetic Recording Heads", *Trans. IRE-PGA*, PGA-9, 16 (Sept.-Oct. 1952).

[6] J. B. Hull, "A Simplified Method for the Performance Measurement of Magnetic Tape Recorders", IRE Convention Record, Part 7, pp. 75-79 (1956).

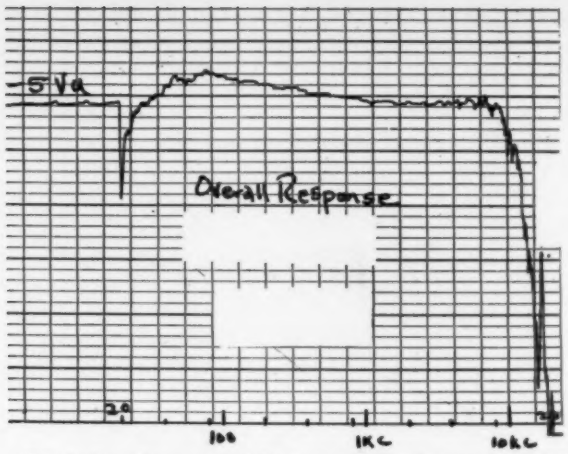

FIG. 4. Overall response of the tape recorder at a record level of -5 VU. The beat tone at the extreme right is due to tape overload.

were to include a "gliding tone" frequency sweep so that playback irregularities at least might be observed on an oscilloscope or voltmeter.

Flutter Measurements

There are a number of commercially available instruments which may be used for this purpose. Perhaps the ones conforming closest to published standards[7] are the Donner Scientific Model 2800 and D&R Model FL-3D. Peak reading devices such as the Furst Model 115 may also be used if suitable corrections are applied to the readings. The readings on all of these meters will be unweighted of course. If the flutter waveform is observed on an oscilloscope, the principal components can be determined and an approximated weighting can be established on the basis of the flutter thresholds previously mentioned. It is hoped that future designs of flutter meters will include these weighting networks in the same way that sound level meters include weighting networks for the Fletcher-Munson effect. It should be noted that present flutter standards call for a "one-way" measurement of flutter—for example on playback only. For this purpose, a test recording having a negligible amount of recorded flutter should be used. It would be desirable if the manufacturers of test tapes would indicate the amount of recorded flutter so that approximate corrections could be made to arrive at "one-way" values of flutter.

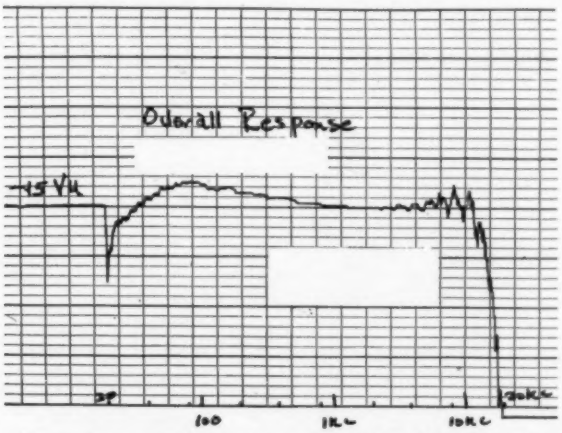

FIG. 5. Same as Fig. 4, but at record level of -15 VU. The beat tone has disappeared but irregularities at the high end possibly due to slight departures from parallelism of the reproduce head pole faces are more pronounced.

[7] IRE Standards on Sound Recording and Reproducing: "Methods for Determining Flutter Content", 1953, 53 IRE 19.S2.

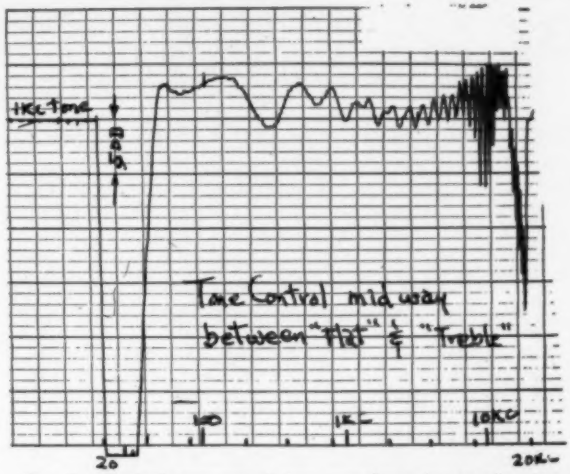

FIG. 6. Typical response of tape recorder using overlap type heads. The irregularities below 2 kc arose during playback. Those above 2 kc appeared on the tape during the recording process.

SUMMARY

It can be seen from the foregoing discussion that evaluation goes far beyond mere performance testing. By a careful consideration of the design of each major component, an insight can be gained into the deficiencies which show up in overall performance tests. Several techniques have been described which have been found useful in uncovering hitherto unrecognized deficiencies in design. It is hoped that more widespread use of these, and more refined techniques, will lead to an overall improvement in quality of all tape recorders.

NOTE: The opinions or assertions contained in this paper are the private ones of the author and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service.

Note on Reverberation Chambers*

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A FACTOR not discussed in my recent paper on reverberation chambers[1] concerns the reverberation characteristic of such enclosures, that is, the variation of reverberation time with frequency therein. In rooms built of concrete, the reverberation period at and near 100 cycles may very likely be twice as long as at 500 or 1000 cycles. The reason for this is that the absorptivity of concrete, 6" thick and well reinforced, is approximately 0.01 at and near 100 cycles, becoming 0.02 in the mid-range. To overcome this condition of boominess, it is desirable to install ¼" thick plywood panels backed by a layer of rockwool and placed 2" above the floor by means of 2" × 4" timbers. A 50 sq. ft. panel in a 2000 cu. ft. room is usually sufficient.[2] Such a panel resonates near 100 cycles, and hence becomes strongly absorptive, while above that frequency its absorptivity tends to become but a fraction of that at resonance. The result is that in the region from 50 to 2000 cycles the reverberation time is essentially constant.

Above 2000 cycles the air-absorptivity of the chamber becomes effective, with the result that the reverberation times become increasingly shorter at the higher frequencies. There is very little that can be done to overcome this condition. Indeed, at 10,000 cycles no room can be built with a reverberation time longer than 1.25 seconds regardless of its volume or the material used for the walls. This may be shown by examining the so-called Sabine reverberation time equation

$$T = 0.05\,V/(A + 4mV)$$

where T is the reverberation time in seconds, A, the total room absorption in sabins, V, the room volume in cu. ft., and m, the air absorption in the room in ft^{-1}.

If the total wall absorption, A, in the room is assumed negligibly small (the term "wall" includes the ceiling and floor), this equation simplifies to

$$T = 0.0125/m.$$

Now, for generally encountered relative humidities of less than 40% and normal temperature (68° F), m at 10,000 cycles can be no smaller than 0.01. Hence, the reverberation time at that frequency can be no longer than 1.25 sec. Figure 1 shows the frequency dependence of air absorption for various percentages of relative humidity at room temperature.[3] Figure 2 shows the absorption characteristic of ¼" plywood backed by 2" of rockwool.

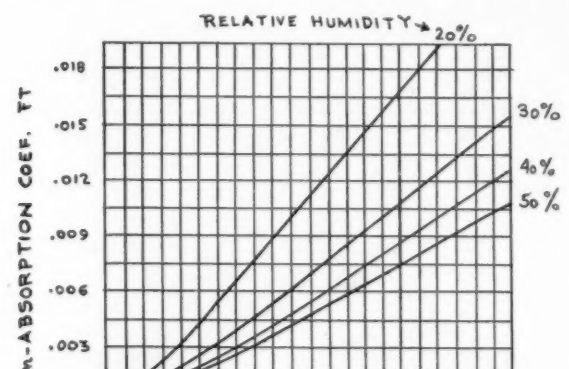

FIG. 1. Frequency dependence of air absorption for various percentages of relative humidity at room temperature (after Knudsen, 1931).

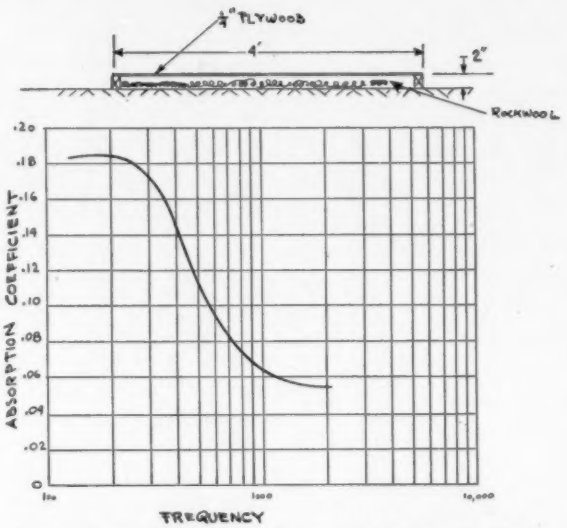

FIG. 2. Top: Detail of ¼" plywood floor (or wall). Bottom: Corresponding frequency dependence of absorption coefficient.

* Manuscript received December 8, 1957.

[1] M. Rettinger, *J. Audio Eng. Soc.*, 5, 18 (1957).

[2] Alternatively, the panel may be mounted on one of the walls.

[3] Extrapolated by the writer from: V. O. Knudsen, "The Effect of Humidity Upon the Absorption of Sound in a Room," *J. Acoust. Soc. Am.*, 3, 120 (1931).

JOURNAL REPRINT

The following paper originally appeared in the May and June 1957 issues of the British journal *Wireless World*, and is reprinted here with the kind permission of its publishers. It considers in great detail, and in the opinion of the Editor, definitively, the interrelated problems of pickup design, stylus pressure, and record wear. Since his appearance in these pages last year, which aroused a great deal of interest, Mr. Barlow has increased his reputation in this country, so that he needs no further introduction.

Limiting Factors in Gramophone Reproduction*

D. A. Barlow, M.Sc.†

1. Plastic Deformation and Wear of Groove Walls

THE STYLUS TIP in a gramophone pickup is usually spherical and much more rigid than the record, so that the problems of determining the deformation of the record groove wall have much in common with those associated with hardness tests such as the Brinell, in which a ball is pressed into the surface to be tested. Under light loads any material will deform elastically, giving a small area of contact. On releasing the load the material springs back to its original position undamaged. With increasing load, the yield stress of the material will be reached and permanent plastic deformation will begin; on releasing the load the material will not return exactly to its original position, i.e. the record is damaged.

The equations for the elastic range are well known and were deduced by Hertz; they have been expressed in convenient form by Hunt.[1]

$$p_m = \frac{0.45\, E_1^{\frac{2}{3}}\, W^{\frac{1}{3}}}{R^{\frac{2}{3}}}$$

$$\text{or } W = \frac{11\, p_m^3 R^2}{E_1^2}$$

Where p_m is mean bearing pressure between contacting surfaces in kgm/mm²

$E_1 = E/(1-\sigma^2)$

E = Young's modulus of record material (kgm/mm²)

σ = Poisson's ratio of record material

W = Load on stylus in grams

R = Stylus radius in mils (0.001 in.).

Because of the complex stress system, yielding occurs at a value of $p_m = 1.1$ times the simple tensile or compressive yield stress of the material. Hunt[1] quotes 11 milligrams as the limiting load for no plastic deformation for a stylus of 1-mil radius on vinyl. Although the stylus is supported by both groove walls at low signal levels, at extreme amplitude or acceleration one wall will be taking most of the load. As this is applied at about 45° to the surface, the playing weight must be increased by $\sqrt{2}$ before yielding can commence, i.e. to about 16 milligrams. In a modulated groove the stylus is in contact not with a flat surface but with concave and convex groove walls. This would reduce the load required for yielding by a factor of 0.77 if the driving wall were convex and the trace radius approached the stylus radius. However, at high frequencies where the trace radius may be small the inertia of the pickup will be a controlling factor rather than the stiffness, so that the load will be taken entirely by the concave outer wall (Fig. 1).

As the load on the indenter (stylus) is increased beyond the elastic range, yielding occurs not at the surface but below, at a distance of about half the radius of the circle of contact. With further increase in load, deformation will gradually spread throughout the area under the indenter. Eventually, plastic deformation of the surface will commence at the surface. With further increase in load, plastic deformation occurs over the whole of the area of contact (the condition has been termed "full plasticity") when the contact pressure is about three times the yield stress of the material. Further increase in load does not appreciably affect the contact pressure. This is the condition in normal indentation hardness testing, where the load must exceed the

* Reprinted, by permission, from *Wireless World*, 63, 228-230, 290-294 (1957).

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[1] Hunt, F. V., *J. Audio Eng. Soc.*, Vol. 3, No. 1, Jan. 1955.

[2] Davies, R. M., *Proc. Roy. Soc.*, Vol. 197, A1050, 22 June 1949.

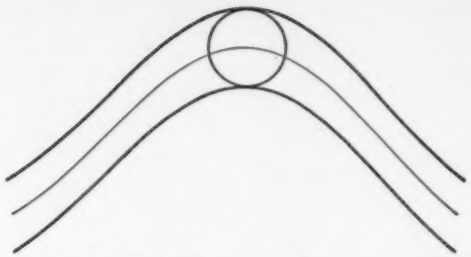

FIG. 1. Stylus supported by convex and concave groove walls.

minimum value for full plasticity for reliable hardness readings to be obtained.

From Hunt's results, the minimum load for full plasticity is 6-10 grams with a 1-mil stylus on a vinyl surface (Hunt's Fig. 2). Many commercial pickups therefore operate in the fully plastic range, and must cause considerable damage to the groove (Fig. 2). If each groove wall were deformed equally at all parts of the waveform, this would give no distortion and would not be serious. However, as the load is not taken equally by each wall, the deformation will be unequal, giving distortion of the waveform, with a decrease of low-frequency signals (where stiffness is operative) and an increase of high frequencies (where inertia is operative). Similar effects occur due to the elastic deformation of the groove walls, but in most if not all commercial pickups the elastic effects will be small compared with the plastic. A possible method of obtaining equal deformation of both groove walls would be to play the virgin record first at twice the normal tracking weight at a very low speed, so that the pickup arm could follow the whole of the wave form with negligible lateral loads, but this would hardly be practicable.

The ideal pickup would work entirely within the elastic range (16 mgm). Although it may not be possible to construct such a pickup it might still be possible to limit plastic deformation to the interior of the material, so that the surface of the grooves is undamaged.[3] The limiting tracking weight would be that at which plastic deformation just commenced at the surface. Unfortunately, this point cannot as yet be calculated. Under any stress system, all materials yield according to some function of the shear stress. The shear stress contours in a material under an indenter at the moment of sub-surface yielding are shown in Fig. 3; they will vary somewhat with the Young's modulus and Poisson's ratio of the material. The shear stress at the surface is 0.33 of the shear yield stress, and is proportional to the cube of the load while the whole of the material is elastic. To obtain surface yielding therefore, the load will have to be raised by some unknown factor, probably greater than $(1/0.33)^3$, giving 0.3 gram for a flat surface, or 0.43 gram for a record groove.

As the record moves under the stylus, the system is not the same as the static indentation case so far considered. Poritsky[4] has shown, for cylinders in contact, that the effect

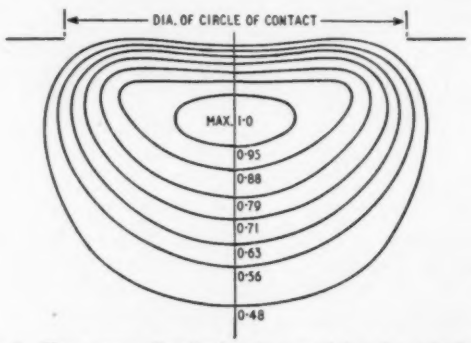

FIG. 3. Shear stress distribution in material under spherical indenter (after Davies[2]).

of an additional tangential force, as represented by friction, is to shift the point of onset of yielding nearer to the surface. The influence of stylus-groove friction would doubtless be similar and would affect yield loads, but if friction is low, as is probably the case, the effect would be small.

Scratch Tests.—Hunt's scratch tests were conducted by dragging 1-mil and 3-mil radius styli over flat vinyl surfaces. No trace was detected below about 6.7 grams for the 3-mil stylus; the corresponding load for the 1-mil stylus should be 0.75 gram, but no tracks were detected below 1.5 grams, probably because of the difficulty of detecting such very fine traces. The limiting loads for plastic deformation just to appear at the surface with a 1-mil stylus will thus be between 0.3 and 0.75 gm for a flat surface, or 0.4 and 1 gm for a pickup, say, half a gram.

Shellac Records.—From hardness tests, the yield strength of shellac is about twice that of vinyl. From cantilever loading tests, the modulus of elasticity of shellac is about three times that of vinyl. The increased yield stress is

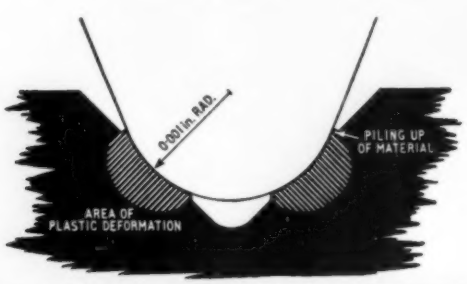

FIG. 2. Stylus-groove contact in the fully plastic range.

[3] Barlow, D. A., *J. Audio Eng. Soc.*, Vol. 4, No. 3, July 1956.

[4] Poritsky, H., *J. Appl. Mech.*, Vol. 17, No. 2, June 1950.

therefore more than offset by the increased modulus, giving a smaller area of contact (and hence higher stresses) for a given load. The limiting load for no plastic deformation of shellac will thus be slightly less than for vinyl (for the same size stylus). For a 2.5-mil stylus the load will be about 90 milligrams, and the corresponding load for plastic deformation to just appear at the surface will be 1.75 grams. Loading tests on shellac with a 2.5-mil sapphire stylus showed tracks at less than 3 grams, corresponding to a pickup weight of about 4 grams. We may thus take the limiting load as about 2½ grams.

It will be noted that at low loads, for a given stylus, shellac will actually be damaged more than the vinyl, but around 15 grams for a 2½-mil stylus the track width or damage will be similar for each material, and above this load the damage to shellac will be less—the track width will be about 0.7 of that on vinyl in the fully plastic range. Shellac is therefore the better material for the old type of heavy pickup, but vinyl will be superior for lightweight pickups. This would explain conflicting reports on the relative damage of vinyl and shellac discs. There is no technical reason why, in these days of lightweight pickups, 78 r.p.m. records should not be made in vinyl.

Deterioration on Repeated Playback.—When any material is deformed the area of contact increases, and, beyond the elastic limit, the material work hardens until it is able to support the load, unless the load is so high as to cause fracture. Once a record has been played at a given weight, provided that this is not too great, there will be no further plastic deformation on continued playback (at the same weight); the record will sound the same as at the first playing, although it may be heavily deformed, and there is no knowing what the virgin record would sound like. The claim that a certain record sounds the same after 1,000 playings as it did with the first playback does not mean that it is undamaged.

It used to be the practice of record companies to monitor the original wax or lacquer disc before plating to make the master. If the original has been damaged in this way, the final record will not sound any different for being played with a very lightweight pickup. It would be interesting to know if the record companies still monitor the original disc before plating now that the original recording is usually done on tape. If we are to take advantage of very lightweight pickups which will not give plastic deformation of the surface not only must we purchase virgin records but it is essential that any monitoring at any stage during manufacture be done with equally light pickups (or with styli that are weaker than the groove walls).

Nevertheless, with heavy pickups progressive deterioration does take place on continued playback. This is due to creep and fatigue. At high stresses the material continues to deform slowly, so that on repeated replay the groove continues to be deformed slightly each time. Fatigue is the fracture of a material by varying or repeated loads at stresses lower than the static strength. As the highest stresses are sub-surface, failure will take place by sub-surface cracking, giving flaking and pitting of the groove walls. This gives the increase in noise characteristic of heavily played records. It is interesting to note that Max[5] obtains this type of failure on repeated playback of polystyrene and occasionally vinyl records at 10 grams load with a 1-mil stylus. If there is a rest period between replays the material partly recovers, and does not fail.

Wear.—Up till now we have been discussing damage or plastic deformation of perfect surfaces, although it is often referred to as wear. Wear may be defined as the attrition of contacting surfaces due to relative sliding. The nature of friction is as follows. Under light loads no two surfaces contact at more than a few high spots or asperities, however accurately they may be finished. Local pressures at these asperities are therefore high, and ploughing, welding and shearing occur on relative motion. This is the normal mode of wear of styli. If there is no bulk surface plastic deformation of a record, the stylus is supported by the asperities, which may be stronger than the bulk material[1,3] and will give a lower rate of frictional wear of record and stylus than a heavier pickup working in the fully plastic range, where the whole of the mating surfaces are in intimate contact. Diamond is known to give lower coefficients of friction with most materials than sapphire or cemented carbide; it might therefore be expected to give less frictional record wear.

Noise.—The noise level will depend on the tracking weight of the pickup as well as on other factors such as sensitivity for degrees of freedom other than lateral. Also Hunt[1] has pointed out that there are the following components in the noise from a gramophone record.

(1) *Surface roughness.* The grooves of modern records are very highly finished, the roughness as low as 50 A.U. (10^{-7} mm). This is as low as is obtainable on the most highly finished surfaces. In the case of shellac, the filler is of course responsible for considerable roughness, and hence noise. This can be reduced somewhat by the use of superfine fillers.

(2) *Welding and shearing of asperities.*

(3) *The associated plastic deformation.* This may also give rise to noise as plastic deformation is not a continuous process, but on a microscale, it occurs by discontinuous slip.

To reduce wear and noise, therefore, improvements can be made only to items (2) and (3), given a homogeneous record material. In addition to using a diamond stylus, the obvious method would be to use polytetrafluorethylene (p.t.f.e.) for the record[1] or the stylus, although its yield

[5] Max, A. M., *J. Audio. Eng. Soc.*, Vol. 3, No. 2, April 1955.

stress and modulus may be too low. This gives low friction with all materials, but if the pickup works in the fully plastic range a coefficient of friction of only 0.04 represents welding of stylus to groove over 25% of the contact area.[3] This will obviously give relatively high wear and noise level, so that the situation with more readily weldable materials, such as vinyl, can well be imagined. Polyethylene usually has a lower coefficient of friction than other plastics (apart from p.t.f.e.) but its yield strength and modulus may be too low; however, Smith[6] has used polyethylene and reports that it gives a lower noise level than vinyl. Polyethylene is said to be too expensive for records; polytetrafluorethylene would be very much more so. It would be interesting to know what proportion of the cost of a record is represented by the plastic and its processing—it has been said that the cost of producing a record pre-war was about 3½d. If so, a more expensive plastic giving lower noise level could obviously be used without appreciably increasing the cost of a record.

Other possible means of reducing friction would be the use of graphite for styli, or porous metal or ceramic impregnated with graphite, oil or p.t.f.e.

Another method of reducing wear and noise due to items (2) and (3) would be by lubrication of the record.[1,3] For this purpose, a solution of calcium petroleum sulphonate in a light petroleum fraction has been suggested. This would be wiped on to the record immediately before each playing, the solvent evaporating and leaving an absorbed film, only a few molecules thick, on the groove walls. This would probably give adequate boundary lubrication, and would not obscure the high frequencies. Flake graphite, as has been used in the past, would not be absorbed on to the groove walls, and would have no effect other than to increase noise by reason of particles trapped under the stylus.

[6] Smith, O. J. M., *Audio Eng.*, Vol. 32, No. 9. Sept. 1948.

2. Pickup Design; Continuity of Stylus-Groove Contact; Tracing Distortion

HAVING EXAMINED, in the first part of this article, the nature of record deformation and wear, we can consider the design of a suitable pickup. The limiting tracking weights are ½ gram for vinyl and 2½ grams for shellac. The lightest commercial pickups track at 2-3 grams for vinyl and 4-6 grams for shellac. It would be difficult to reduce the tracking weight to the desired value for vinyl, but it would be fairly easy to halve the tracking weight for shellac, as the design is in any case easier than for vinyl. If the desired low weight for tracking on vinyl could be achieved, the resultant pickup would doubtless be fragile, and have low output voltage, but before ruling out such a pickup as impossibly difficult and expensive, it should be remembered that only a few years ago pickup manufacturers considered that anything with a tracking weight of less than 30 grams was a fragile, expensive, specialists' instrument. With the advent of microgroove records, and the necessity of reducing tracking weights to about 8 grams, if reasonable record life was to be obtained, pickup manufacturers have produced, apparently without difficulty or complaint, pickups which not only operate at this weight but are fairly cheap and have a high output voltage; even record changers have been redesigned to treat records with more care.

The Arm.—This must have low friction and low inertia, particularly with warped records, and torsional resonance which will influence response must be avoided. A single vertical pivot bearing is at once the simplest and cheapest, is robust, has the lowest friction, and torsional resonance is avoided. If desired, an anti-vibration mounting can be used between head and arm to further reduce the effect of arm resonance. The only disadvantage of the single-point bearing is that very thin flexible leads must be used to reduce drag. To reduce the torque on the arm to a minimum, the armature should be positioned (at the correct angle for minimum tracking error) with the stylus on the axis of the arm (Fig. 4). To obtain the correct tracking weight the arm may be counter-balanced either by a weight or by a spring—in the case of a single pivot, a weight only is possible. The weight is much more convenient and more easily adjusted, but it is sometimes argued that a spring is better in that it saves weight and hence inertia of the arm. However, although the saving of weight is considerable, the saving of inertia is very small. Thus if the head is of mass m, distant l from the pivot, its moment of inertia about the point is ml^2; this must be counterbalanced by a mass of say $5m$, distant approximately ⅕ from the point, having a moment of inertia of $5m \times (\frac{1}{5})^2 = \frac{ml^2}{5}$, i.e., for the convenience of using a counter-balance as opposed to a spring there is an increase of only 20% in the inertia. As the inertia of the tube forming the arm has been ignored the increase in the total inertia will be somewhat smaller. As the inertia of the arm will usually be only a fraction of

that of the head, particularly if a magnetic head is used, there is no point in making the arm absurdly flimsy.

The Head.—The limiting weight of the head will depend on the degree of warping of the record to be played, the accuracy of the centre hole and the accuracy of the turntable. The inertia of a 60-gram head is not excessive at a tracking weight of 2 grams; it is thought, therefore, that at a tracking weight of ½ gram, a head weight of 15 grams would not be excessive. In a magnetic head it is doubtful whether this weight of magnet would give saturation in the size of gap likely to be used, but sufficient flux to give useful output should be obtainable. With shellac records, with the greater weight allowable, there should be no difficulty. Where a crystal movement is used there will be less difficulty in attaining a small head weight. The type of movement used is partly a matter of choice. The moving coil system is easily designed and has fewer objections than moving iron and crystal systems. The coil would preferably consist of several turns of fine wire giving a higher output voltage than a ribbon or single turn, so as to be well above the hum level picked up by the leads.[7,8] The coil would preferably be a bifilar push-pull winding, feeding into a centre-tapped coupling transformer, thus reducing hum. A strain-gauge system in which the electrical resistance of a fine wire is varied by the strain it receives is attractive, as it is simple and can be made in small sizes. However, circuit arrangements are a little complex, and the signal level would almost certainly be so low that noise and hum would be serious problems. Carbon composition strain gauges would be unsatisfactory, due to self-generated noise. Other methods, such as magneto-striction and frequency modulation, would seem to offer no advantages. The recently introduced magnetomotive system[9] consisting of a moving magnet with a stationary coil on a soft iron core is attractive, as the moving parts are simple and robust and high impedance with high output voltage is obtainable without a coupling transformer.

The tracking weight has been discussed by Mallett.[10] It is governed by three factors, the lateral stiffness, the lateral inertia and the vertical stiffness. The lateral stiffness is operative at low frequency so that the inner surface of the groove will take most of the load; at high frequencies the inertia of the moving parts is operative and the outer wall of the groove takes the load. In a complex waveform stiffness or inertia may be operative over different parts of the wave, but the full load will be taken at any instant by only one groove wall, so that stiffness and inertia loads are

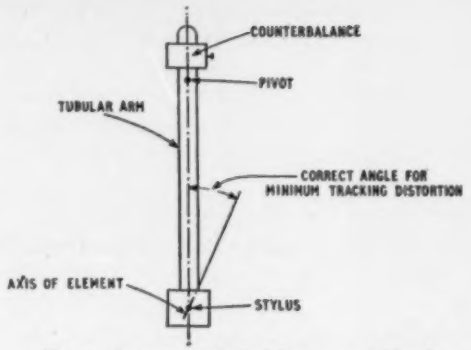

FIG. 4. Arrangement of pickup arm and head.

complementary. The maximum stiffness load is reached at maximum amplitude; the maximum inertia load may not always be reached at maximum amplitude, depending on the waveform; the maximum load due to vertical stiffness when vertical amplitude is greatest is at the mid-point of the wave. These three components of load, therefore, lateral stiffness, lateral inertia and vertical stiffness, are largely complementary rather than additive. Vertical inertia is not in itself important as will be shown later. Longitudinal movement of the stylus must be a minimum, otherwise distortion and rounding off the steep wave fronts will occur. Lack of longitudinal rigidity is the probable reason for needles trailing rather than being set vertically.[11] A vertically set needle will vibrate longitudinally if it is not rigid in that direction. The maximum angle of the trace to the direction making a tangent to the groove at the stylus contact must be less than the half angle of the groove (approx. 45°), otherwise the stylus will ride up the groove wall regardless of tracking weight. The angle of the trace in the 33⅓ r.p.m. extended play records appears to approach this limit as a result of the greater amplitudes employed.

Lateral Stiffness.—This must be such that the lateral load for the maximum recorded amplitude is not greater than the tracking weight, i.e., lateral compliances must be more than 6×10^{-6} cm/dyne for vinyl and 4×10^{-6} cm/dyne for shellac. This should not be difficult to arrange.

Resonances.—There will be a number of resonances due to the mass of the armature, head, etc., with the lateral, vertical, and longitudinal compliances of the suspension, and record-stylus. The armature should be sufficiently rigid longitudinally for resonances with this compliance to be ignored. The other resonances are examined below. Any damping material must be added with caution, as it may cause intermodulation distortion.[12]

Lateral Low-frequency Resonance.—This is the resonance

[7] Baxandall, P. J., Letter, *Wireless World*, Sept., 1950.
[8] West, R. L., Letter, *Wireless World*, Sept., 1950.
[9] Wittenburg, N., *Philips Tech. Rev.*, Vol. 18, Nos. 4/5 and 6, 1956/57.
[10] Mallett, E. S., *Electronic Eng.*, May, 1950.
[11] Rabinow, J., and Codier, E., *J. Acous. Soc. Amer.*, Vol. 24, No. 2, March, 1952.
[12] Roys, H. E., *Audio Eng.*, May, 1950.

of the mass of the head and arm and the lateral stiffness of the movement, and the frequency is given by

$$f_1 = \frac{1}{2\pi\sqrt{M_p C_a}}$$

where M_p is the lateral effective mass at the stylus of the head and arm (gm), C_a is the lateral compliance of the movement (cm/dyne).

The effective mass at the stylus is:

$\frac{I}{l^2}$ where I is the moment of inertia about the particular axis, and l is distance of axis from stylus (cm).

This resonance has been used in cheap pickups to boost the bass; it should, of course, be below the recorded range in a high-quality pickup. For vinyl with a head weight of 15 grams, the resonance would be at about 17 c/s; for shellac with a 75-gram head, the resonance would be about 9 c/s.

Lateral Mid-Frequency Resonance.—This is the resonance of the mass of the movement (coil or armature) with its own lateral stiffness (restoring force), and generally occurs at the mid-frequencies. Unlike most other resonances, it is not deleterious. It is a series resonance and at the resonance frequency the stylus point impedance tends to zero (Fig. 5). It simply means that at this frequency no power is required to move the armature except that required by damping. The physical significance of this can be easily seen—the stylus will always try to move at this frequency so that at lower frequencies it tends to return to the mid-point faster than the trace allows, so that it is always pressing on the inner wall of the groove; at high frequencies it tends to return to the mid-point slower than the trace allows, so that it is always being forced back by the outer wall of the groove. This resonance is given by

$$f_2 = \frac{1}{2\pi\sqrt{M_a C_a}}$$, where M_a is lateral effective mass of element at stylus.

Lateral High-frequency Resonance.—This is the resonance of the mass of the element with the compliance of the record and stylus. It is well known that if this frequency is in the audio range, excessive noise will result from shock excitation of this resonance, and there may be accompanying distortion, even if the resonance is thoroughly damped. This resonance is given by

$$f_3 = \frac{1}{2\pi\sqrt{M_a C_s}}$$, where C_s = lateral compliance of stylus and record materials (cm/dyne).

For this resonance to be above say 20 kc/s, M_a must be less than about 1 milligram for vinyl and 3 milligrams for shellac.

Lateral Inertia.—The maximum accelerations recorded are about 1500 *g* for microgroove records and 500 *g* for 78 r.p.m. records.[13] The corresponding limiting lateral effective mass at the stylus is 0.33 milligram for vinyl, which would be hard to achieve, and 5 milligrams for shellac, which would be easy to achieve.

Vertical Stiffness.—The need for vertical movement is of course to allow for the pinch effect. The groove is cut with a chisel-edged stylus and traced with a spherical stylus, as a consequence of which the stylus of an ideal pickup must move vertically at twice the frequency of the trace. The maximum vertical amplitude is about 1/9th of the lateral for microgroove and 1/6th for 78 r.p.m. records. The vertical stiffness must therefore be not greater than 9 times and 6 times the lateral stiffness respectively, i.e., a compliance of 0.67×10^{-6} cm/dyne in each case.

Vertical Resonances.—Although the pickup may not generate any voltage for vertical movement, vertical resonances are best avoided in the recorded range, or, rather, at twice these frequencies, as the vertical movement takes place at twice the recorded frequency of the trace. Where the lateral loads are not shared equally by each groove wall, as is always the case except at zero amplitude, any vertical forces will cause movement of the stylus not vertically but at some angle—in extreme cases up and down the side of one of the groove walls, and will thus generate a signal, even though true vertical movement generates no signal. The normal vertical movement may therefore generate a signal, although it may be very small, but vertical resonances may be serious.

Vertical Low-frequency Resonance.—This is not the resonance of the mass of the head with the vertical compliance of the movement or cantilever, and should be below the recorded range. It will be about 50 c/s for vinyl and 22 c/s for shellac (corresponding to lateral recorded frequencies of 25 and 11 c/s) for the pickup considered here.

Vertical High-frequency Resonance.—This is the resonance of the vertical effective mass at the stylus point with the compliance of stylus and record, and should be above the recorded range, i.e., above 40 kc/s (corresponding to 20 kc/s lateral). The vertical compliance of record and stylus is unknown, but will probably be about half the

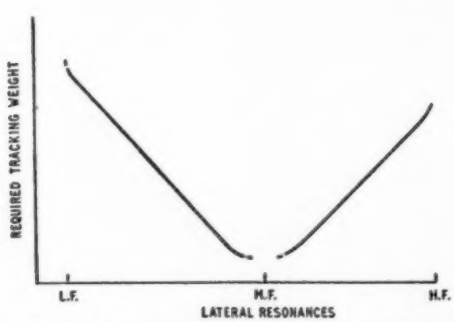

FIG. 5. Effect of lateral resonances on required tracking weight.

[13] Cosmocord Ltd., Private communication.

lateral, as the load is now taken by both walls of the groove. The limiting vertical effective mass at the stylus will thus be about 0.5 mgm for vinyl and 1.5 mgm for shellac.

The above two resonances will influence each other's frequencies slightly, but as they are a long way apart the interaction will be very small and can be ignored. With suitable design there will be no other vertical resonance, and the stylus will maintain contact with the groove at all times, except when severe tracing distortion occurs, due to overmodulation, when the trace radius approaches the stylus radius. When this occurs, and contact with the groove is not maintained, there will obviously be acoustic rattle or needle-talk, and the output may be affected. In addition, when the stylus point is free, there may be a further vertical resonance, falling in the mid-frequencies (see later). The vertical inertia of the system is not, in itself, of importance, as the high-frequency resonance is above the recorded range.

Cantilever Movements.—To achieve the above very small effective vertical masses in practice, a cantilever type of movement is essential, as only the cantilever and stylus contribute to the vertical mass, the axis of the generating element being vertical. In most other designs, the whole of the element must move vertically, and the total mass is limited to the allowable vertical mass. The cantilever movement has the added advantages that vertical movement is obtained with the minimum of longitudinal movement, and the system can be easily designed to minimize damage due to accidental dropping on the record. The use of a cantilever, however, introduces its own lateral, vertical and torsional resonances. The lateral resonance can probably be avoided, as the cantilever must be stiff laterally if appreciable signal loss is to be avoided. The torsional stiffness could be increased for a given cantilever mass by making it of tubular form, and its magnitude reduced by placing the stylus tip as near as possible to the axis of the cantilever. Vertical resonance of the cantilever will occur when the stylus is not in contact with the groove, and in any practical design this resonance will fall within the audio range. However, when the stylus tip is in contact with the groove, and provided the generating element itself has negligible vertical compliance, there will be no resonance in the audio range. Considering vertical movement only, the system has two degrees of freedom, Fig. 6(a), and the only resonances will be the low and high frequency ones already listed. If there is appreciable vertical compliance between armature and head, the system will have three degrees of freedom, Fig. 6(b), and there will be three resonances, the additional one of the mass of the armature with the cantilever compliance being within the recorded range. The armature vertical compliance can be made very small if the top end of the armature forms a cup-and-cone bearing with the head; in the case of a torsional crystal element it may be firmly fixed to the head.

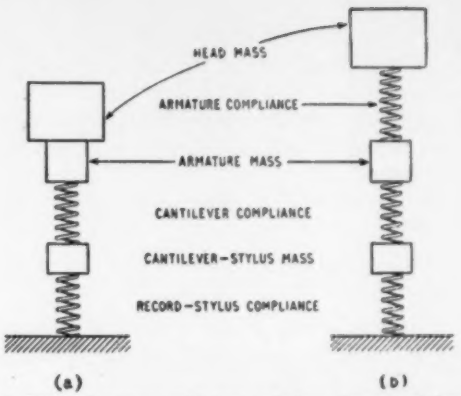

FIG. 6. Vertical systems with two and three degrees of freedom.

The cantilever would best be made in a hard rigid plastic, perhaps phenol-formaldehyde, as this would have the greatest stiffness/weight ratio of any practical material, this being proportional to modulus/(density)^2. Sapphire and diamond would be too heavy for tips, at least for microgroove, so that a one-piece replaceable plastic moulding could be used for stylus plus cantilever.

Soft Styli.—In passing, it should be noted that the usual objections to soft needles will not apply here; as the yield stress and modulus of the stylus will be appreciably greater than those of the record material, there will be no serious deformation of the stylus, and fairly accurate tracing with reasonable life would be obtained. Conditions would bear no relation to those of the conventional thorn under, say, 40 gm playing weight, under which the point is deformed to contact almost the whole of the groove, with consequent distortion and top loss. The other conventional objections to thorn are the possible embedding of either sharpening or other dust with consequent abrasive wear of the grooves, the thorn acting as a lap. The possibility of dust from sharpening being embedded is much exaggerated; every day in industry, millions of sandpapering and grinding operations are carried out on all types of material and particles of abrasive are virtually never embedded in the work. It is possible to get embedding of abrasive, particularly with certain soft and ductile metals, but it occurs only with unsuitable grinding conditions, and virtually never occurs with the free-working non-metallic materials. Regarding the embedding of ordinary dust, if the record is cleaned sufficiently well each time for the noise due to dust to be inaudible, it is difficult to see how such dust as remains could become audible, and the rate of wear, if any, would be extremely small. Further, it is by no means certain that abrasive wear by such means actually occurs; for lapping to take place, the lap must normally be much softer than the material to be lapped. In the present case, the plastic will be harder than vinyl or (unfilled) shellac.

The relatively low modulus of soft styli, compared with sapphire or diamond, will increase the stylus-record compliance, which will lower the lateral and vertical high-frequency resonances. Again, a high-modulus plastic must be chosen, when the effect will probably be slight, but, if necessary, a further reduction in mass at the stylus point must be made.

Tracing Distortion.—This is by far the most serious form of distortion in record reproduction. It can be very distressing on shellac records, and is tolerable on vinyl only by reason of the elastic deflection of the groove walls, which reduces the tracing distortion but introduces a further type of distortion which is less serious. Severe record damage will result from overmodulated traces, however light the pickup. When the trace radius is equal to or less than the radius of the stylus at the point of contact with the walls, the stylus is required to change its direction instantaneously, which requires infinite deceleration and acceleration thus giving groove deformation and rattling. On 78 r.p.m. records an elliptical stylus is essential to reduce tracing distortion to tolerable limits. Thus a 3-mil bottom radius/1-mil lateral radius stylus can be used, reducing the tracing distortion by a factor of 6; the tracking weight must be reduced to about half that for a 2.5-mil stylus. With microgroove records no such course is possible, and tracing distortion is more serious than on 78 r.p.m. records played with an elliptical stylus.

The high tracing distortion of microgroove records is due to the excessive high-frequency pre-emphasis used, as the de-emphasis in playback only partly offsets the distortion caused by pre-emphasis. The NAB characteristic, giving 16 db rise at 10 kc/s is particularly bad—to quote Hunt, it "effectively guarantees excessive distortion." As a result, the A.E.S. standard curve, giving 12 db rise at 10 kc/s, was adopted. The purpose of the pre-emphasis is of course to reduce surface noise; as the noise of good vinyl records is barely audible, it seems that even the 12 dB rise could be reduced without surface noise becoming objectionable. The noise level is reduced by about 6 dB for the 12 dB boost; if this were reduced to 6 dB, there would be an increase of 3 dB in noise level, which would be barely noticeable, with a reduction in tracing distortion by some factor approaching 4, which would be a very noticeable improvement. If there were no pre-emphasis, the noise level would be 6 dB higher than the A.E.S. standard, which would still be very much lower than shellac, and tracing distortion would be drastically reduced. This point has been well made by Viol.[16]

An attractive alternative to dropping pre-emphasis would be 78 r.p.m. microgroove records—there would still be sufficient playing time per side that breaks would come between movements of symphonies, etc. The use of high-frequency pre-emphasis perhaps has more justification for shellac records where surface noise is high, but even here the gain may be largely offset by the increased tracing distortion. In any case, with a lightweight pickup, say less than 10-15 gm, there is no reason why 78 r.p.m. records should not be made in vinyl.

Dutton[17] has shown that for a given maximum level of tracing distortion, disc diameter, and average groove spacing, there is an optimum speed of rotation of the turntable, giving the longest playing time. He states that at a groove speed of 16 in./second, on standard 78 r.p.m. records, tracing distortion is apparent (this is rather an understatement), but that quality is not noticeably impaired at 22 in./sec. The corresponding velocities for microgroove records (presumably allowing for high-frequency pre-emphasis, etc.) are stated to be lower by a factor of 1.6, i.e., 10 in./sec and 13.75 in./sec respectively; at this latter speed distortion is about 4% and it increases very rapidly to about 16% at 10 in./sec. On the basis of a minimum speed of 10 in./sec., a 12-in. disc gives a maximum playing time of 22 minutes at an optimum speed of about 33⅓ r.p.m. However, if we take the preferred minimum speed of 13.75 in./sec., the maximum playing time is about 16 minutes at a speed of about 45 r.p.m.; 33⅓ r.p.m. gives a playing time of 15 minutes, and 78 r.p.m. gives 14 minutes. In other words, on the basis of work done by a well-known record manufacturer, if good quality is to be obtained, 15 minutes is about the limit of playing time, for a 12-in. disc, and the speed of rotation makes very little difference. In fact, the differences are so small that the trouble and expense of changing speeds and obtaining new turntables (usually more expensive than for 78 r.p.m., owing to the need to reduce rumble) was quite unjustified—the microgroove vinyl 78 r.p.m. record was the obvious choice, and speeds were doubtless changed only because the Americans had already done so. It has been argued that the slower speeds have the advantage of giving more margin for squeezing in an extra minute or so to enable the item to be completed; this is justified if the passage is a quiet one, but this does not often happen at the conclusion of a work. The fact that most 12 in. l.p. discs run for 20-25 minutes, and some for as much as 32 minutes, shows that this advantage is in fact a very serious disadvantage if high quality is to be obtained; with 78 r.p.m. microgroove discs, excessive squeezing in would be prevented by the label. There are even some gramophone enthusiasts who consider that on certain l.p.'s, the musicians were persuaded to hurry through the work in order to squeeze it on to one side of a very long playing l.p. disc, when it would have been better to take two sides.

[14] Watts, C. E., Reported in *Wireless World*, Dec., 1949.

[15] Pierce, J. A., and Hunt, F. V., *J. Acous. Soc. Amer.*, Vol. 10, No. 4, July, 1938.

[16] Viol, F. O., *Proc. I.R.E.*, Vol. 38, No. 3, March, 1950.

[17] Dutton, G. F., *Wireless World*, June, 1951.

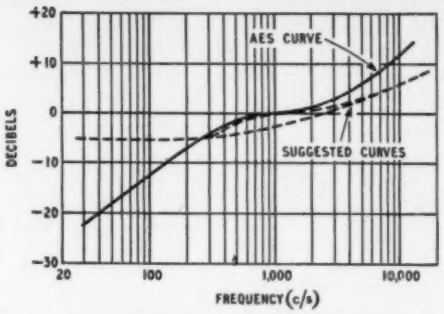

FIG. 7. Suggested revision of recording characteristics.

If high-frequency pre-emphasis were not used on micro-groove discs, it would be possible to go to a lower minimum groove speed, say 8½ in./sec, for good quality, when a playing time of about 26 minutes would be obtained on a 12-in. disc, run at 22 r.p.m.

On the subject of recording characteristics, it is interesting to note in passing that Hunt[15] has pointed out that the maximum output for both speech and music drops off at rather more than 6 dB per octave below 250-300 c/s, i.e., the usual bass cut in recording is unnecessary. The advantage of no bass cut is obvious—less equalization required, i.e., less waste of precious output volts from the pickup, with the elimination of hum and rumble problems. There is some doubt about published curves for maximum output, as it is possible that transients and organ notes reach higher levels; nevertheless it would be interesting to know if bass cut is really necessary to avoid overcutting, or whether it is simply a hang-over from the days of acoustic recording, when the recording equipment unavoidably gave such a cut. The suggested recording characteristics are given in Fig. 7.

Returning to the problem of tracing distortion, together with pinch effect and the need for vertical motion of the stylus, the whole difficulty would disappear if the original groove were impressed with a spherical stylus, a duplicate of the reproducing stylus, instead of being cut with a chisel. As the area of contact of the groove with the stylus would now be greatly increased, deformation and wear from existing pickups would be almost eliminated. The limiting tracking weight for an impressed groove is difficult to calculate but would be about 0.9 gm for vinyl for *the elastic range*. With a comparatively slight reduction in existing tracking weights of the best pickups, there would be no damage whatsoever to record grooves and frictional wear of both groove and stylus would be very low. It might be necessary to use very close tolerances on dimensions of both recording and reproducing styli, to avoid an oversize stylus being forced into the groove, or an undersized one from "skating," but this would be a very small price to pay, especially as the reproducing stylus would be virtually everlasting for normal users. Alternatively, a V-groove could be impressed with a conical stylus, which would give a greater contact area and hence even higher limiting tracking loads. By making the bottom radius of the reproducing stylus larger than that on the recording one, skating would be avoided and a universal stylus becomes possible.

An impressed type of groove would doubtless require considerably more power for recording than a cut groove, but this might be offset by recording at a high temperature, either by means of a heated stylus or by heating the blank. Thus the normal hard type of recording wax or lacquer could be impressed while hot and soft. There are doubtless other difficulties, but the advantages to the record user would be so great that every effort should be made to produce impressed-groove records.

The impressed type of groove, with the high tracking weights possible without serious groove damage, makes the acoustic gramophone once more possible as a high-quality reproducer. Although there may be many limitations on the quality obtainable, some improvement in design is doubtless possible, and it should be remembered that the best acoustic gramophones have a clarity of reproduction which is not matched by many commercial radiograms.

Book Reviews

Sonics

T. F. Hueter and R. H. Bolt, John Wiley & Sons, New York, 1955, xi + 456 pages, illustrated, $10.00.

The applications of mechanical wave motion occur in two main fields, communications acoustics and industrial acoustics. In the former, wave motion is used primarily to communicate between human beings, usually with the interposition of electroacoustic and electronic devices. Industrial acoustics deals with the interactions between mechanical wave motion and matter, as illustrated by sonic testing and processing. In sonic testing we are interested in determining the properties of a material by observing the alterations it causes in a wave. On the other hand, in sonic processing we look for alterations in matter caused by a wave. These two topics, with supporting material on vibration and radiation theory, and properties of transducers, receive intensive treatment in this text. An indication of the scope of treatment is given by citing the chapter headings: Introduction, Basic Principles, Radiation, Piezoelectric Transducers, Magnetostrictive Transducers, Physical Mechanisms for Sonic Processing, Devices and Techniques for Sonic Processing, Principles of Sonic Testing and Analysis, and Acoustic Relaxation Mechanisms in Fluids.

The text is characterized by the application of analogous circuits based on the force-voltage analogy; mks units are used throughout. The approximately 220 illustrations, 24 tables, and 400 references help to balance the nearly 400 equations. However, practically all the analytical background needed to understand the theoretical treatment is supplied by undergraduate electric circuit theory.

Much of the information presented has already appeared, scattered throughout the journal literature. In recognizing the importance of industrial acoustics as a new and growing field of engineering, the authors have gathered together a wealth of material which provides as up to date a summary as is possible. Particularly valuable treatments are given, for example, to radiation pressure, the near field of radiators, barium titanate and magnetostriction transducer operation, behavior of acoustic lenses, commercially available devices for sonic processing and testing, forces on particles in intense sound fields, cavitation, and the theory of absorption in liquids. The authors correctly point out that many industrial acoustics applications require high-intensity rather than high-frequency sound and are often more efficient at audible frequencies. In the opinion of the reviewer, the growth of industrial acoustics has been hampered by the overselling of ultrasonic sound as a somewhat magic and mysterious phenomenon.

The reviewer unreservedly recommends this text to anyone working in industrial acoustics, a field which can well use the abilities of audio engineers as well as acoustical physicists.

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Electronique Industrielle (Industrial Electronics) (In French)

G. Goudet, Editions Eyrolles, 61 Boulevard St. Germaine, Paris 5, France, 1955, 635 pages, 417 illustrations, 5,740 francs (about $16.40)

In a manner analogous to industrial acoustics, industrial electronics is concerned with testing, processing and control by electronic devices. Since the same basic principles apply to both the communications and industrial applications, a book devoted to the latter will contain more than a smattering of the former. Thus, the first three-quarters of the text proper of this French book is devoted to a thorough and fundamental treatment of the theory involved. A detailed knowledge of complex variable theory is required, together with lesser knowledge of electromagnetic field theory, quantum-electronic theory of the solid state, and differential equations. Electron tubes and circuits get the major attention, with relatively brief mention of transistors and magnetic amplifiers. This first portion of the book is in essence an excellent summary of communications electronics.

After such an auspicious beginning it is somewhat disappointing to note the small amount of discussion devoted to the applications aspect of industrial electronics. Of the total of some 600 pages of true text, about 8% is devoted to electronic optical devices; 3% to high frequency heating; the same to photocells; 6% to ultrasonics; and 8% to servos and regulating mechanisms. Much more attention is given the details of the devices concerned than the actual applications. Nevertheless anyone active in these fields will find plenty of nuggets of information.

The above criticisms would be less valid if the title of the book were "Fundamentals of Industrial Electronics", or something similar. Because of the fundamental nature of the book, it is likely that its principal appeal will be to the communications physicist or engineer rather than to the industrial electronics engineer. The absence of an index (a defect common to many French texts) is offset by an unusually detailed table of contents placed at the end of the book. A bibliography of papers and books is also included.

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The New High Fidelity Handbook

Irving Greene and James Radcliffe, introduction by Deems Taylor, Crown Publishers, Inc., New York, 1955, 193 pp., 250 illus., $4.95.

Deems Taylor (in introduction) says: "Greene and Radcliffe are two gentlemen whose knowledge of Hi Fi is only slightly less than awesome." Harold C. Schonberg (2nd introduction) says:

"Audio response is dependent upon too many imponderable factors."

Greene and Radcliffe say:—

p3; "The designation music system signifies a degree of quality which is not normally found in a standard commercial radio set console."

p14; "Low frequency arm resonance causes distortion in the *loud* passages."

p38; "There is no distortion worse than turntable rumble or record scratch which is easily understandable considering . . . ."

p39; "A good check aside from listening, is to handle the amplifier loosely."

p41; "It is almost impossible to hear absolutely nothing. Don't be overcritical; allow some margin and make sure that this sound is absent in the presence of music."

p41; Amplifier specs . . . "0.1db from 20 to 20,000 cps."

p42; Loudspeaker specs . . . "Variations of a few db (in unspecified bandwidth) are unimportant."

p42; "This division of energy obviates the directional characteristics of the treble frequencies which then are dispersed through the type of projector used."

p48; "When the low frequency speaker was developed it was aptly named a woofer to signify a low throaty sound like the woof of a dog."

p49; "The answer is purely logical" and "The response would be effective only at one axis in front of the tweeter."

p50; "Various types of speakers have been used to serve as a *low frequency* woofer."

p52; "If the crossover were not used the effect of reproduction would be less desirable than that of a cheap speaker."

p53; "To the music lover the higher percentage efficiency becomes apparent when two speakers are demonstrated." "The answer is yes and no."

p53; "This word of caution is added so you will not solder . piece of wire across the voice coil terminals."

p55; "A frequency is a vibration which moves a given number of times per second."

p56; "Actually the closest approach to perfect sound reproduction is realized with a loudspeaker mounted into an indefinite baffle." "Infinite dimension is a volume of one-third to one-half the wavelength of the lowest frequency note audible to the ear."

p57; "Plan well and wisely where the speaker is to be installed; it is the most important Hi Fi component and should be given the most consideration." This reviewer failed to find a single suggestion as to why to put it where.

p70; "Publications are fussy about items advertised for sale and screen them carefully" and twenty lines further "Everything advertised as Hi Fi just isn't."

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For a 7 in. x 10 in. working area, the smallest desirable letter height is 0.14 in. (made with a Leroy pen 0 or Wrico pen 7).

Recommended, too, are the following line widths:

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For grid rules—½ point or 0.007 in.
For reference lines—1 point or 0.014 in.

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More complete information on lantern slide dimensions is given in American Standard Dimensions for Lantern Slides, Z38.7.19-1950.

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